Concawe

Review

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Foreword

Evaluation of pathways to decarbonise transport, simulations of the impact of our products on air quality, evaluation of the safety of our industrial and supply activities: the articles in this edition of the Concawe *Review* target our traditional area of interests and are at the heart of the European Green Deal objective of climate neutrality, and a safe and clean environment.

The first article summarises a study launched by Concawe to assess the effects of fuel quality on diesel passenger car and commercial vehicle emissions. Several diesel fuels, with different qualities including different proportions of biofuels, have been tested on cars and heavy-duty vehicles with different Euro norms to evaluate the interactions between fuel quality and vehicle technology, and the effects on CO_2 and NO_x emissions.

The second article is part of Concawe's Low Carbon Pathways project: it examines the specificities of the maritime transport sector, and develops and compares three scenarios whereby the International Maritime Organization's (IMO's) ambition to reduce global maritime emissions by 50% in 2050 would be met through a combination of ship technology improvements and low-carbon fuels mix.

The third article builds on the findings of the earlier Concawe urban air quality studies to examine how concentrations of the major urban pollutants (NO_2, PM and ozone) would vary under different emission reduction scenarios, and to assess the practicability of achieving compliance with the current and future European Union air quality limit values.

The final article celebrates an anniversary: Concawe has been publishing regular reports on European oil pipeline safety and environmental performance statistics for 50 years! These reports have contributed to a better understanding of these issues, and have allowed pipeline operators to develop best practices to reduce the number of spills and accidents, including those caused by theft. Given the success, and the need to continuously improve inspection, maintenance and supervision practices on an ageing pipeline network, there is no doubt that we will be celebrating a 100-year anniversary in 2072!

Jean-Marc Sohier
Concawe Director

Contents

As both vehicle technology and emissions legislation continue to evolve, Concawe has conducted studies to examine the multidimensional effects that fuels can have on greenhouse gases (GHGs) and pollutant emissions from diesel passenger cars (PCs) and commercial vehicles (CVs).

Three diesel passenger cars spanning Euro 5, 6b and 6d-TEMP were tested in the PC study over the Worldwide harmonized Light-duty Test Cycle (WLTC), and a Euro VI bus and Euro V delivery truck were tested in the CV study over the World Harmonized Vehicle Cycle (WHVC) and Transport for London Urban Inter-Peak (TfL UIP) cycle. Test fuels used in the studies were common to both the PC and CV work: an EN 590-compliant B5, hydrotreated vegetable oil (HVO) sustainable paraffinic fuel, a 50/50% v/v blend of the aforementioned fuels, a low density petroleum-derived B5, a B30 containing 30% v/v sustainable fatty acid methyl ester (FAME) and the same B30 additised with a high dose of cetane number improver (CNI).

The expected tank-to-wheels reductions in CO_2 were detected from low-density fuels versus EN 590 B5 due to their lower carbon intensity. Some benefits in pollutant emissions from low-density fuels were detected in older vehicle technologies but are reduced below any detection threshold in later technology vehicles due primarily to exhaust after-treatment (AT) effectiveness, and an engine-out benefit in NO_x in the Euro VI bus manifested as a reduction in consumption of SCR (selective catalytic reduction) reductant (AdBlue). The increased NO_x emissions from B30 reported in some previous studies were not evident in any vehicle except the Euro 5 PC with no NO_x AT. The addition of CNI to B30 did not counter the increase in NO_x observed in one vehicle, and it is postulated that this would be broadly the case in modern vehicles. N_2O emissions from the vehicles fitted with NO_x AT catalysts (lean NO_x traps and SCR) can contribute around 5–7% of the total GHGs emitted, whereas this is less than 0.5% in vehicles without NO_x AT, highlighting the challenges of optimising vehicle technology to minimise both GHG and pollutant emissions.

Overall, this work illustrates the complex and evolving interactions between fuels and vehicle technology affecting emissions.

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This article provides a summary of a 'deep dive' study into the future development of emissions from international maritime transport. The study is part of Concawe's Low Carbon Pathways project, and has been undertaken by Ricardo on behalf of the Oil and Gas Climate Initiative (OGCI) and Concawe.

The context for the study is the International Maritime Organization's level of ambition to reduce the total carbon emissions from international shipping by 50% in 2050 compared to 2008 levels, as well as reducing the carbon intensity of international shipping by at least 40% by 2030 and 70% by 2050 (again compared to a 2008 base year).

The study reviewed available literature, and interviewed multiple stakeholders, to identify the technologies and alternative fuels that are available to decarbonise international shipping.

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How additional actions in the road transport sector could improve air quality in Europe — an extension of the Concawe urban air quality studies 31

This article presents results from a modelling study carried out to examine how concentrations of the major urban pollutants (i.e. nitrogen dioxide (NO_2), particulate matter (PM) and ozone (O_3)) would vary under different emission reduction scenarios, and to assess the practicability of achieving compliance with the current European Union (EU) air quality limit values (AQLVs), with road transport being the core focus of the research.

The study builds on the findings of the earlier Concawe urban air quality studies which are used here as base case. Through a scenario sensitivity analysis, the study aims to give insights into the question of what additional actions can be considered to improve compliance with AQLVs in the future — an important question from a policy point of view. A number of road transport scenarios were examined, assuming various rates (up to 100%) of substitution of diesel-powered road transport vehicles with electric-powered vehicles. Although road transport emissions were the primary focus of the study, additional scenarios were explored which examined emissions reductions from other sectors so that the contribution of road transport to improving compliance could be considered in context with other sources.

The major findings of the study indicate the following:

- All 'beyond the base case' road transport scenarios offer a further small and time-limited (between 2020–2025) improvement in NO_2 compliance. In the longer term (post 2025), the already-legislated measures as described in the base case result in almost full compliance of NO_2 with the current EU AQLVs across Europe. The impact of further NO_x measures, either on road transport or on other urban emissions sources (domestic sector) will be negligible.
- Any remaining exceedances of NO_2 would require targeted, city-specific measures based on a thorough source attribution analysis, and any EU-wide and/or national reductions measures will no longer be effective.
- Lowering the EU NO_2 AQLV to align closely with the revised World Health Organization (WHO) air quality guideline value will impose significant EU-wide non-compliance issues.
- Any additional measures to mitigate exhaust PM emissions from road transport will only offer a limited further improvement of $PM_{2.5}$ compliance and only in the shorter term, while post 2025 the impact will be negligible.
- The most effective strategy for reducing $PM_{2.5}$ concentrations is related to actions concerning further emission controls or fuel substitution for solid fuel burning in the domestic sector. This will be important in addressing the significant and widespread $PM_{2.5}$ non-compliance issues that will likely occur in the EU with any future move to closely align the current EU AQLV with the WHO air quality guideline value.
- Ozone (O_3) compliance will not show any further improvement in any of the 'beyond the base case' road transport scenarios. Indeed, further reductions in NO_x emissions and the accompanying loss of NO titration could eventually lead to an increase in the number of O_3 exceedance days, making compliance even more challenging.

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Contents

Fuel effects on modern diesel passenger car and commercial vehicle emissions

Introduction

As Europe progresses through the energy transition, it is expected that battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) will represent a growing share of the vehicle fleet, while internal combustion engine vehicles (ICEVs) will still be present, at least because of the legacy fleet. The renewable component of fuels used in ICEVs has the potential to reduce the well-to-wheel (WTW) greenhouse gas (GHG) emissions and may affect the physical-chemical properties of the fuels. Bearing in mind that fuel effects on engines are often multidimensional, they must be thoroughly understood through rigorous study. As both vehicle technology and emissions legislation continue to evolve, Concawe has conducted studies to examine the effects that fuels can have on emissions from diesel passenger cars (PCs) and commercial vehicles (CVs). The latest round of studies were completed in 2020 by Ricardo UK (PC) and VTT Finland (CV). The results of these studies have been published in the literature[1,2] and this article aims to summarise the findings.

Concawe has conducted studies to evaluate the effects that fuels can have on emissions from diesel passenger cars and commercial vehicles. This work illustrates the complex and evolving interactions between fuels and vehicle technology affecting emissions. The results of the studies have been published in the literature, and this *Review* article summarises the findings of this work.

Authors

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Test fuels

The test fuels, F1–F6 (fuels 1 to 6), and rationale behind their inclusion are outlined in Table 1, and further detail is given in the referenced publications.[1,2] A prerequisite was that the fuels could be used as 'drop-in' fuels[1] and, as such, any effect on local or wider GHG emissions could be realised in the existing vehicle fleet — with the caveat that compatibility of these fuels with the existing vehicle fleet would require further specific consideration. Hydrotreated vegetable oil (HVO) is described as paraffinic diesel fuel (PDF). F1 (EN 590 B5) was used as the comparator fuel for F2 (low-density B5), F3 (PDF) and F4 (PDF50). F2, the low-density B5, was used as the comparator for the B30 fuels F5 and F6 because they shared a common petroleum diesel component and therefore enabled the effects of the high FAME content (and CNI[2]) to be isolated.

[1] The term 'drop-in fuels' has no commonly agreed definition, but is defined for the purpose of this study as fuels which are compliant for use with the existing vehicle technology for a short duration of time (typically a few vehicle tests), with no guarantee that the tested fuels are compliant with the existing fuel specifications, and no guarantee that the tested vehicles can comply with the emission standards when tested with out-of-specification fuels.

[2] Cetane number improver

Table 1: Overview of, and rationale for, the test fuels

Fuel code/ description	To evaluate the impact of:	Density (kg/l)	Cetane number	C/H/O ratio (%m/m)	Total aromatics (%m/m)	T95 (°C)	Net heating value (MJ/kg)	Net heating value (MJ/l)	CO_2 intensity (gCO_2/MJ)
F1: EN 590 B5 5% v/v UCOME[a] and 95% v/v conventional European diesel	Comparator fuel representing current European diesel	0.845	52.0	86.4/ 13.1/ 0.5	34	356	42.7	36.1	74.2
F2: Low-density B5 5% v/v UCOME and 95% v/v low-density conventional refinery streams (jet + diesel)	Lower-density/ higher-H/C ratio petroleum-derived fuel	0.805	51.4	85.3/ 14.1/ 0.6	7	351	43.2	34.8	72.4
F3: PDF Renewable paraffinic diesel fuel (HVO[b])	Paraffinic fuel composition	0.764	79.6	84.6/ 15.4/ 0	0.1	289	44.2	33.8	70.3
F4: PDF50 50% v/v EN 590 B5 and 50% v/v PDF	Paraffinic stream as a blending component	0.805	67.0	85.6/ 14.1/ 0.3	17.9	338	43.4	34.9	72.4
F5: B30 30% v/v UCOME and 70% v/v low-density conventional streams	Sustainable high FAME content	0.825	52.4	83.6/ 13.1/ 3.3	5.1	348	41.7	34.4	73.4
F6: B30+CNI B30 + 0.52% 2-EHN cetane number improver	CNI effect on NO_x emissions	0.826	65.8	83.6/ 13.1/ 3.3	4.5	350	41.7	34.4	73.4

[a] used cooking oil methyl ester [b] hydrotreated vegetable oil

Test vehicles

Test vehicles were selected to represent a range of exhaust after-treatment configurations, and span Euro 5/V and Euro 6/VI standards as technologies that are abundant in the European fleet up to and including the latest vehicles.

Passenger cars

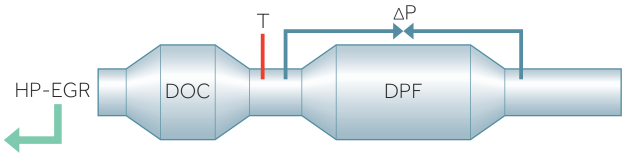
Vehicles were sourced second-hand from the market. Technical details regarding their powertrain and after-treatment configurations are given in Table 2 and Figure 1.

Table 2: Passenger car test vehicle details

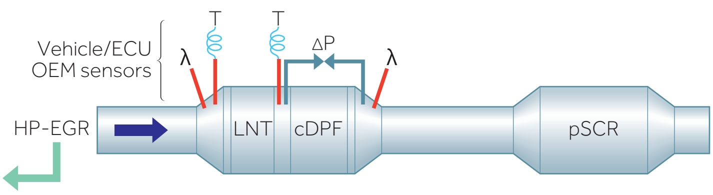
	Car A	Car B	Car C
Emissions certification	Euro 5b	Euro 6b	Euro 6d-TEMP
Year of registration	2013	2016	2017
Engine capacity (litres)	1.6	1.5	1.5
Vehicle mileage at start of test (km)	91,000	10,000	6,000

Figure 1: Passenger car test vehicle details

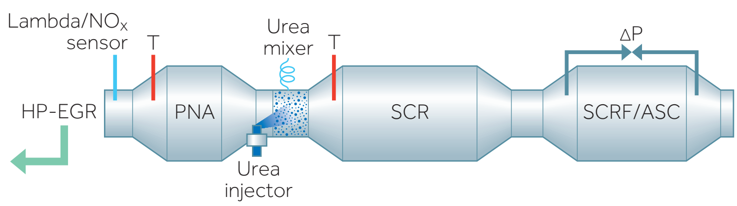
Car A
- Euro 5 certified on NEDC
- HP-EGR
- DOC
- DPF



Car B
- Euro 6b certified on NEDC
- HP-EGR
- LNT
- cDPF
- pSCR



Car C
- Euro 6c-TEMP, certified on WLTC and RDE
- HP-EGR
- PNA
- Urea-SCR
- SCRF



Notes:

ASC: ammonia slip catalyst

cDPF: coated diesel particulate filter

DPF: diesel particulate filter

DOC: diesel oxidation catalyst

ECU: electronic control unit

HP-EGR: high-pressure exhaust gas recirculation

LNT: lean NO_x trap

NEDC: New European Driving Cycle

PNA: passive NO_x adsorber

pSCR: passive selective catalytic reduction

RDE: Real Driving Emissions test

SCR: selective catalytic reduction

SCRF: selective catalytic reduction — filtered

T: temperature sensor

λ: lambda sensor

ΔP: differential pressure

Commercial vehicles

Vehicles were rented from the Finnish market. Details are given below in Table 3 and Figure 2.

Table 3: Commercial vehicle details

Description	Heavy-duty bus	Medium-duty delivery truck
Emissions class	Euro VI	Euro V
Year of registration	2016	2012
Engine cylinders/ displacement (dm^3)[a]	L6[b] / 7.7	L4[c] / 4.6
Peak power (kW)	235	162
Peak torque (Nm)	1200	850
Fuel injection equipment	Common rail, exhaust-mounted injector for after-treatment heating	Common rail
Exhaust after-treatment	HP-EGR, DOC, DPF, SCR, ASC	HP-EGR, DOC
Unladen weight (t)	14.65	6.0
Gross vehicle weight (t)	24.75	10.0
Vehicle mileage at start of test (km)	344,000	300,000

Notes:

[a] Dm^3 = cubic decimeter: 1 cubic decimetre = 1 litre.

[b] L6 = inline six-cylinder engine;

[c] L4 = inline four-cylinder engine

HP-EGR: high-pressure exhaust gas recirculation

DOC: diesel oxidation catalyst

DPF: diesel particulate filter

SCR: selective catalytic reduction

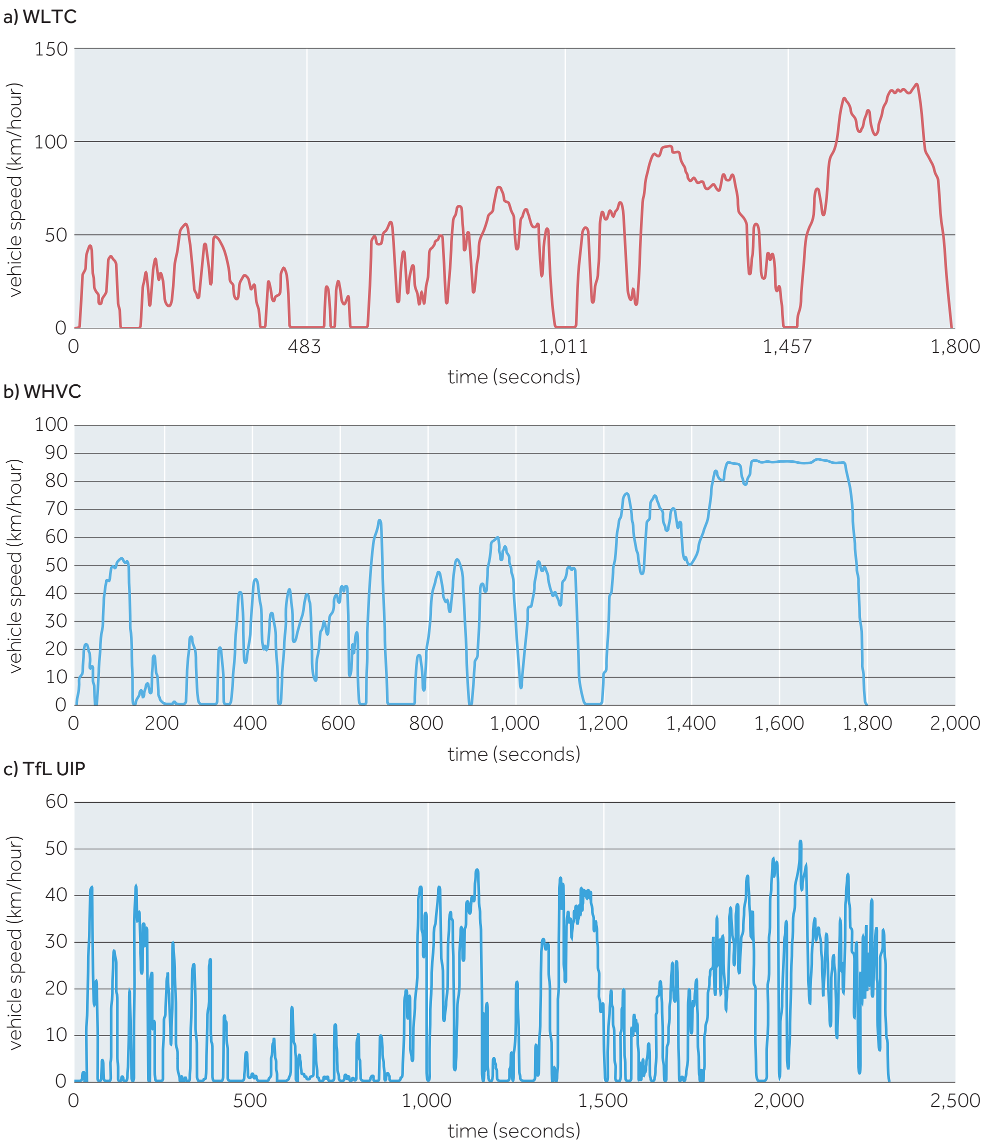
ASC: ammonia slip catalyst

Figure 2: Commercial vehicles on a chassis dynamometer

Test execution

The passenger cars were tested over the Worldwide harmonized Light-duty Test Cycle (WLTC) from cold start, with a minimum of two repeats per test fuel over a randomised test order. The commercial vehicles were tested over the World Harmonized Vehicle Cycle (WHVC) and the Transport for London Urban Inter-Peak (TfL UIP) test cycle from hot, instead of cold engine start due to operational constraints. The TfL UIP cycle simulates driving in congested urban conditions where emissions control can be more challenging, whereas the WHVC covers a wider range of conditions including motorways. A minimum of three repeats on each test fuel were scheduled in the CV testing over a randomised test order.

Figure 3: Vehicle speed profiles of the WLTC, WHVC and TfL UIP test cycles



Results summary

Full results are given in the referenced publications[1,2] and the most notable results are summarised here. As the results for the CVs were similar over the WHVC and TfL UIP cycles, only results from the WHVC are shown here as this is the more widely accepted test cycle.

Fuels are divided into two subsets for comparison — effects of lower-density fuels (F1 compared with F2, F3 and F4), and effects of oxygenated compounds (F2 compared with F5 and F6). Note that the hatched bars on the figures indicate a statistically significant difference (> 95% confidence interval) from the comparator fuel, and error bars denote the 95% confidence interval itself.

Low-density fuel effects

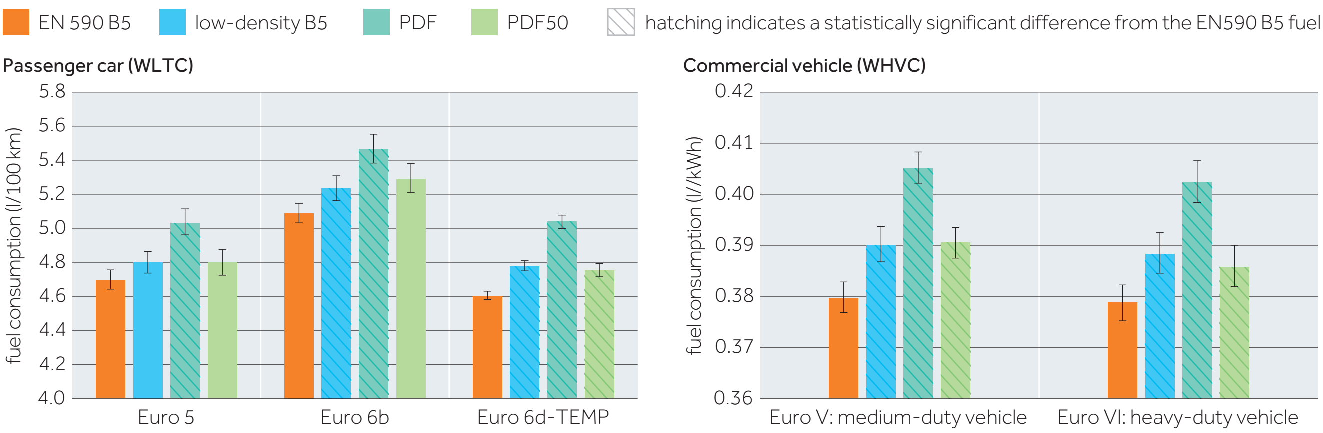
Fuel consumption, CO_2 emissions and total greenhouse gases

As expected, volumetric fuel consumption is higher for the lower-density fuels, and mass fuel consumption is lower, strictly following the fuels' energy content as energy consumption remains unaffected.

Tailpipe CO_2 emissions were reduced for all three low-density fuels in all vehicles versus the EN 590 B5, directly and proportionally resulting from their lower CO_2 intensity. This trend was repeated in the overall GHG emissions.[3]

It was notable that N_2O emissions from the vehicles fitted with NO_x after-treatment catalysts (lean NO_x traps and SCR) contributed around 5–7% of the total GHG emissions, but was < 0.5% from the vehicles without NO_x after-treatment. This highlights the impact and a potential opportunity for optimisation of these technologies which could be addressed in the Euro 7/VII legislation.

Figure 4: Low-density fuel effects on volumetric fuel consumption



[3] Global warming potential 100-year figures for CO_2 equivalent (from the IPCC Fifth Assessment Report, 2014) using the GREET model[3] based on combined emissions of CO_2, N_2O and CH_4 for the PCs, and CO_2 and N_2O only for the CVs because CH_4 was immeasurably low in most tests for CVs.

Figure 5: Low-density fuel effects on CO_2 emissions

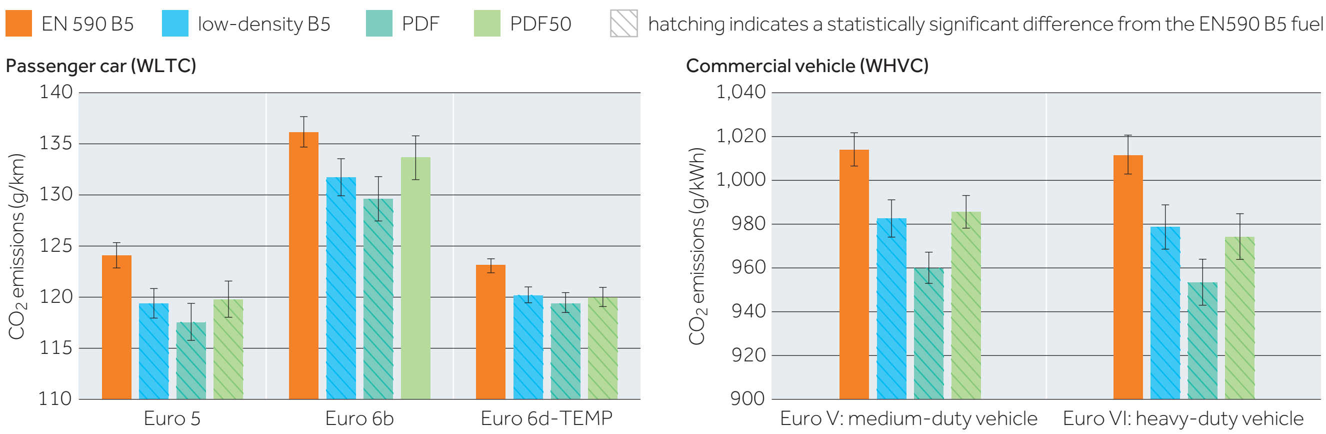
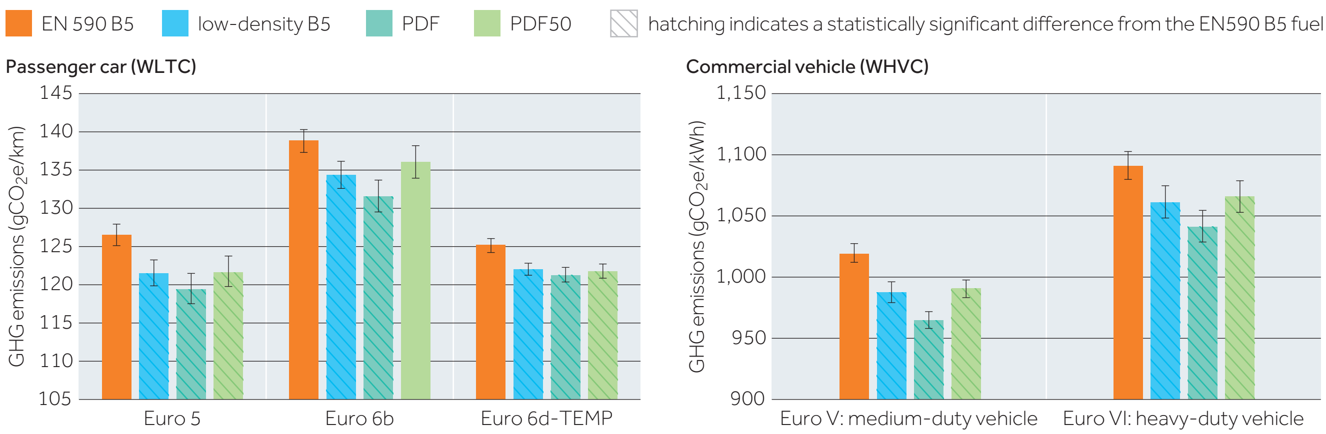


Figure 6: Low-density fuel effects on GHG emissions



NO_x and AdBlue

There were no statistically significant fuel effects on tailpipe NO_x in any vehicle (see Figure 7 on page 12). However, several engine-out[4] measurements in the Euro 6d-TEMP PC and Euro VI CV showed benefits of low-density fuels engine-out, although benefits were inconsistent between vehicles (Figure 8, page 12). SCR reductant (AdBlue) consumption was measured from the CV and this correlated with engine-out NO_x and showed a clear benefit for PDF (Figure 9, page 12).

It should be noted that the NO_x emissions from the Euro 5 vehicle were extremely high versus the Euro 5 limit (180 mg/km). It is postulated that this results from testing over the WLTC, which is more demanding than the New European Driving Cycle (NEDC) over which the vehicle would have been calibrated and certified. This outlines the gap between homologated and real-life emissions for this vehicle (as well as for other vehicles of the same generation, as demonstrated by other groups) whereas this gap is absent from modern vehicles (Euro 6d-TEMP vehicle in this instance).

[4] Pre-exhaust after-treatment

Figure 7: Low-density fuel effects on NO_x emissions (results show no significant fuel effects at the tailpipe)

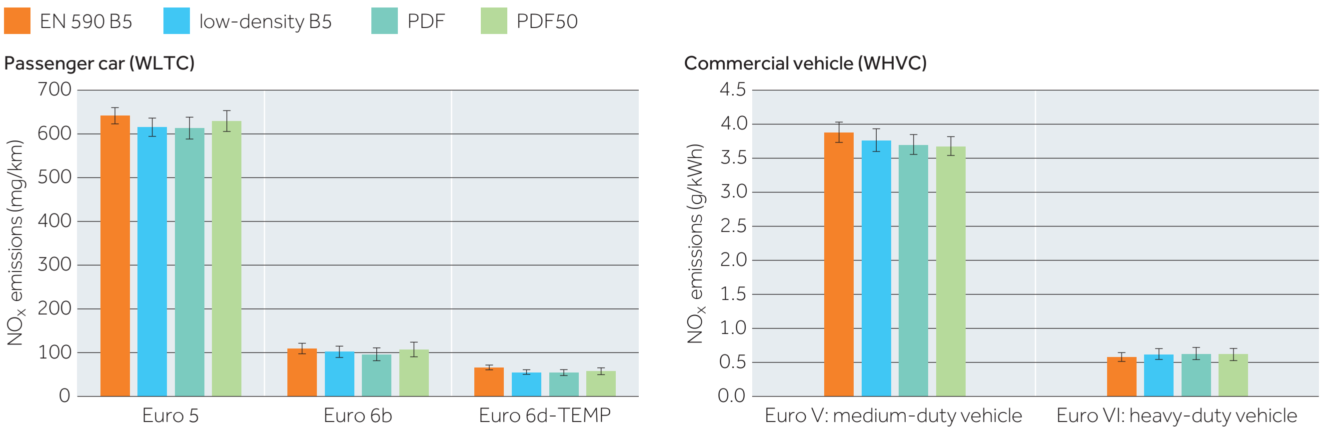


Figure 8: Low-density fuel effects on NO_x emissions — engine-out versus tailpipe

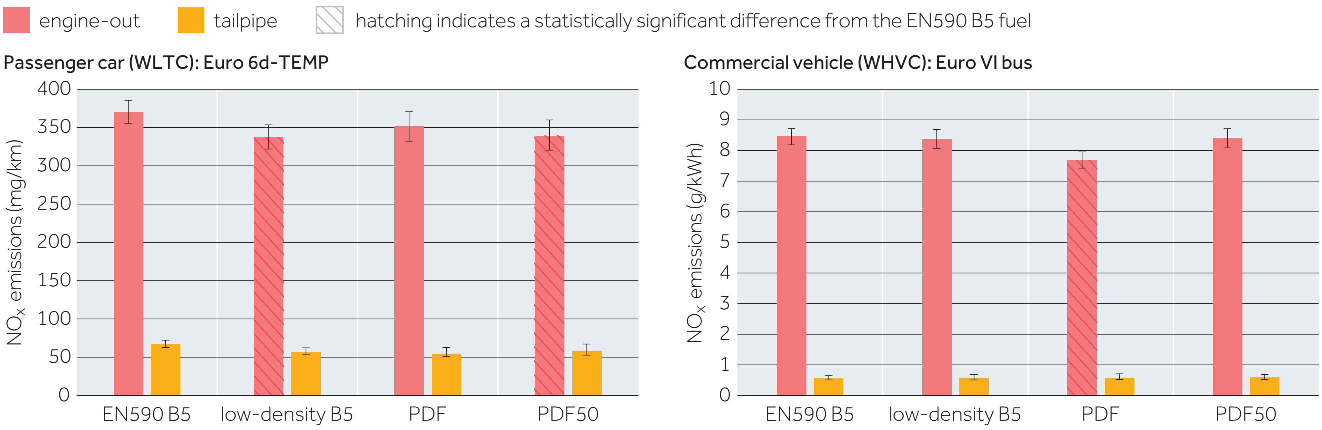
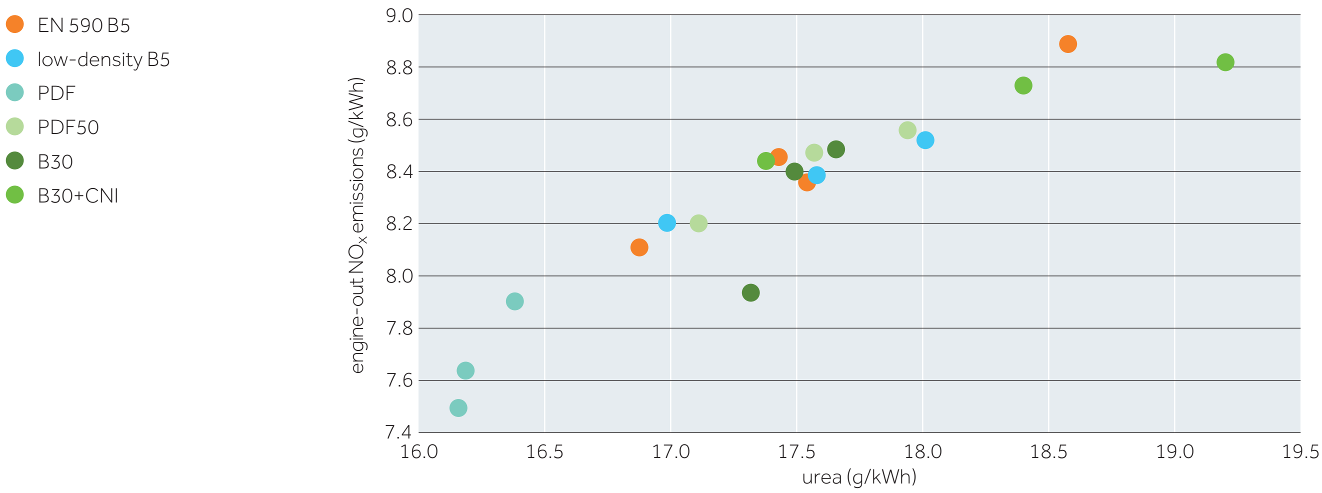


Figure 9: Correlation between engine-out NO_x and AdBlue (urea) consumption — Euro VI bus, WHVC
(results show a reduced AdBlue consumption for PDF)



Summary of other results with the low-density fuels set

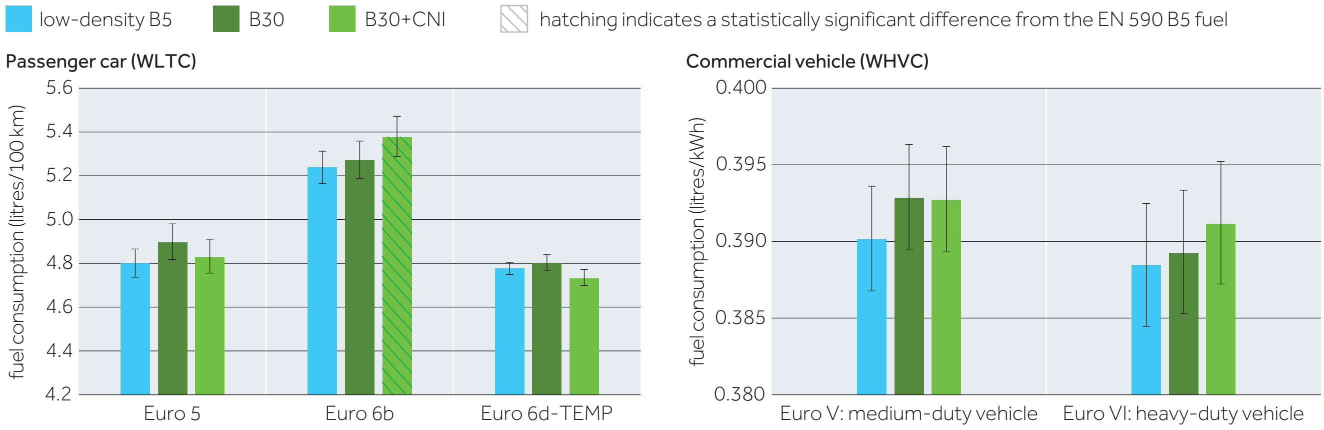
- No statistically significant effects on tailpipe PM and PN emissions were observed, except for reduced PM emissions with some low-density fuels from the Euro V truck which had no DPF.
- Significant effects were observed on CO and HC in some cases, tending to be reduced with low-density fuels.
- Ammonia (NH_3) emissions were close to immeasurable in vehicles without urea-SCR systems, and not directly affected by fuel type in all vehicles.

High FAME content fuel effects

Fuel consumption and CO_2 emissions

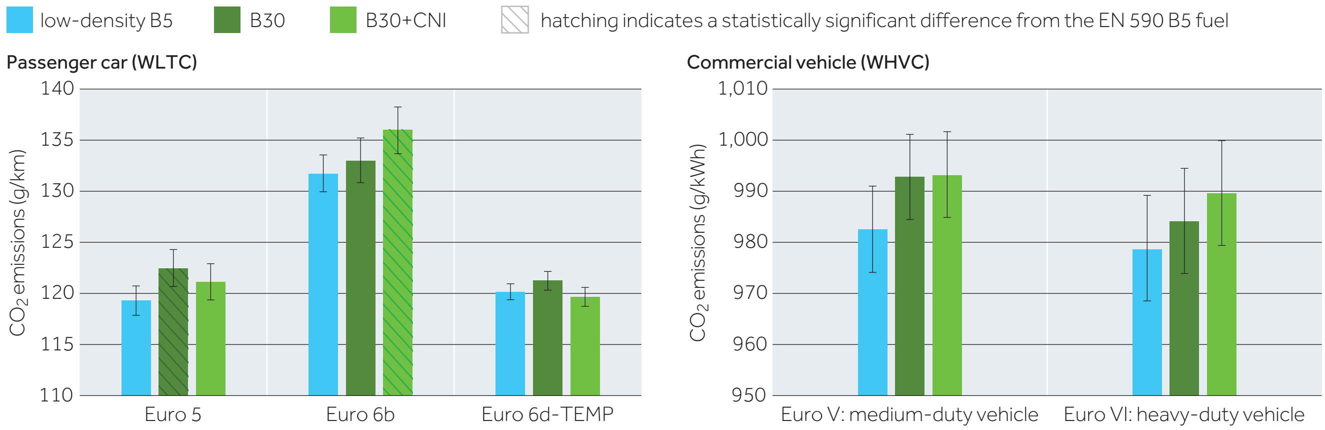
Volumetric fuel consumption was generally unchanged with B30 compared to the low-density B5 fuel, due to there being no impact of FAME on volumetric energy content or efficiency (Figure 10). While it may seem surprising that the volumetric fuel consumption is not increased with B30, this is due to the relative low density of the B5 comparator fuel, and the large increase in density when up-treating FAME content to B30, which contributes to keeping the volumetric energy content constant in spite of lowering the energy content by mass. Under more traditional circumstances, adding high volume levels of FAME to petroleum diesels at constant EN 590 density range usually results in an increase in volumetric fuel consumption.

Figure 10: Effects of increasing FAME content (B5–B30) on volumetric fuel consumption



There was a significant increase in CO_2 emissions in the Euro 5 PC with B30 and with the Euro 6b PC with B30+CNI (Figure 11). As this effect related to B30 is not consistent between the tested vehicles (three vehicles remain unaffected), the stated increase could be due to a quirk of the individual vehicle calibration where de-optimisation of fuel metering has occurred with the high-oxygen-content fuel.

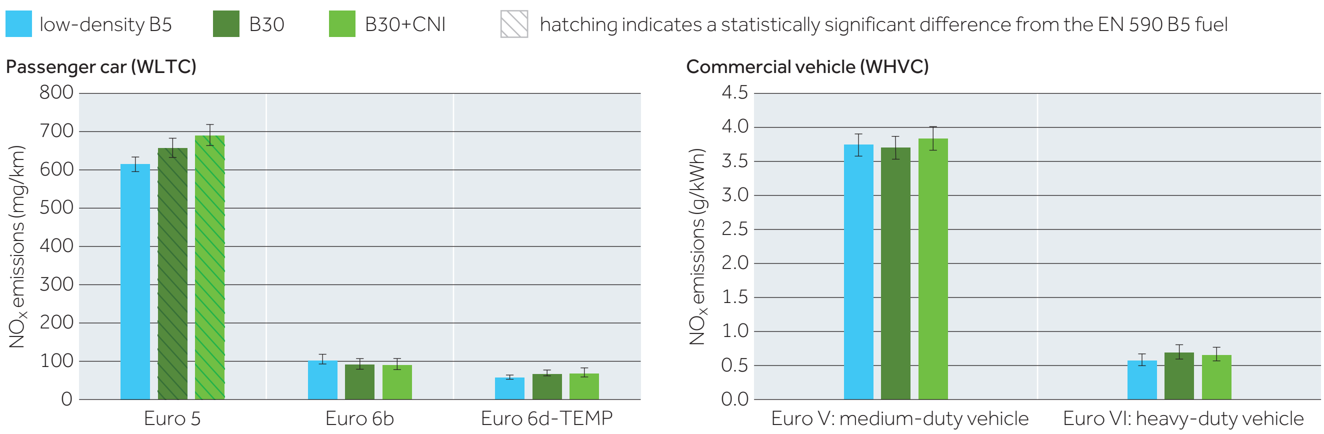
Figure 11: Effects of increasing FAME content (B5–B30) on CO_2 emissions



NO_x emissions

The increased NO_x emissions from B30 reported in some previous studies[4,5] were not evident in any vehicle except the Euro 5 PC with no NO_x after-treatment and, as mentioned earlier, in the case of conspicuously high tailpipe NO_x emission levels under WLTC test conditions (Figure 12).

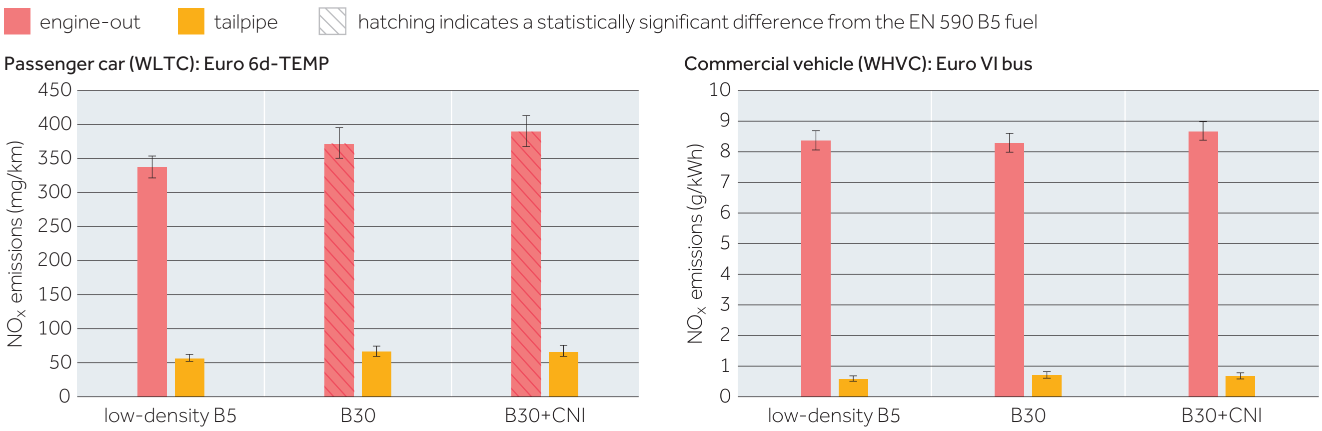
Figure 12: Effects of increasing FAME content (B5–B30) on NO_x emissions
(results show that NO_x emissions only increase with FAME content in the Euro 5 PC, and that the addition of CNI does not mitigate this effect)



Furthermore, the addition of 2-EHN to B30 did not counter the increase in NO_x emissions observed; indeed, NO_x was higher with the CNI. This differs from what was determined and practised historically for HD vehicles in California[5] where CNI was mandated in high-FAME fuels to offset NO_x penalties. It is postulated that the ineffectiveness of CNI in this respect would be broadly the case in modern vehicles due to advances in fuel injection technology and multiple injection strategies lessening fuel effects on combustion premix time.

Engine-out NO_x emissions were measured in addition to tailpipe NO_x from the Euro 6d-TEMP PC and Euro VI bus (Figure 13). The results show that engine-out NO_x is higher with B30 than B5 in the PC but there is no significant fuel effect in the bus. In both cases there is no statistically significant fuel effect on NO_x emissions at the tailpipe, illustrating that modern SCR after-treatment systems with closed-loop control of NO_x provide an effective barrier to manage any potential increased engine-out NO_x emissions from high-FAME-content fuels where they occur.

Figure 13: Engine-out and tailpipe NO_x emissionsfor B5, B30 and B30+CNI fuels
(results show that B30 gives significantly higher engine-out NO_x in the PC but not at the tailpipe due to the effectiveness of the SCR)



Summary of other results with the B30 fuel set

- No statistically significant effects on tailpipe PM and PN were observed. The lack of the expected benefit in PM from high FAME content in the non-DPF Euro V truck is explained by the higher-density of the B30 fuel relative to the B5, which has offset the oxygen content effect (leading to better soot oxidation) of the B30.
- Some reductions in HC and CO were observed in the Euro V truck, and in engine-out emissions of the Euro 6d-TEMP PC. This effect is usually expected with higher FAME content which improves the oxidation of these species.
- Ammonia emissions were close to immeasurable in vehicles without urea-SCR systems. Of those with urea-SCR, there were no fuel effects in the Euro 6d-TEMP PC; however, NH_3 emissions were higher with B30 in the Euro VI bus. It is postulated that this is an artefact of the vehicle urea-dosing and ammonia slip catalyst efficiency and not a fuel effect, given that ammonia emissions are almost immeasurable in vehicles without urea-SCR running with B30; it would nevertheless be prudent to monitor for this effect in other experiments.

Conclusions

Concawe has conducted studies to evaluate the effects that fuels can have on emissions from diesel passenger cars and commercial vehicles. The following conclusions can be drawn from these studies:

- The results of these studies align with those from the existing literature on the effects of low-density fuels (e.g. HVO, XTL) and high-FAME fuels (B30) on tank-to-wheel (TTW) CO_2 (i.e. driven by their CO_2 intensity), and engine efficiency (i.e. no significant effect detected) versus an EN 590 B5 comparator fuel.
- Low-density fuels provide some benefits in overall TTW GHG emissions (CO_2, N_2O, CH_4) that reduce their environmental impact.
- In vehicles with sophisticated exhaust after-treatment systems, low-density fuels can provide savings in AdBlue consumption in vehicles equipped with urea-SCR, while they have no significant effect in tailpipe pollutant emissions affecting local air quality (NO_x, PM, HC, CO).
- Modern SCR after-treatment systems with closed-loop control of NO_x provide an effective barrier to manage any potential increased engine-out NO_x emissions from high-FAME-content fuels where they occur. High-FAME (B30) fuels can therefore be deployed in vehicles with advanced after-treatment systems without causing adverse impacts on NO_x emissions, and hence local air quality, reported in some historical studies.
- In some modern vehicles with sophisticated fuel injection systems and calibration, but not equipped with advanced NO_x exhaust after-treatment systems, high-FAME fuels can still lead to increased NO_x emissions. This effect is unlikely to be mitigated with the addition of 2-EHN, as was the case in older technology, because combustion premixing is less sensitive to fuel effects in modern vehicles using advanced fuel injection strategies.
- Ammonia emissions tend to be close to immeasurable in vehicles without urea-SCR systems, and levels are unaffected by fuel properties. In SCR-equipped vehicles there could be a correlation between tailpipe NH_3 and fuel type due to interplay with the after-treatment system. Results of other test programmes should be examined to determine whether this relationship is systemic.
- Nitrous oxide emissions from the vehicles fitted with NO_x after-treatment catalysts (lean NO_x traps and SCR) can contribute around 5–7% of the total GHGs emitted, whereas this is less than 0.5% in vehicles without NO_x after-treatment, highlighting the impact of, and potential opportunity for, optimisation of these technologies especially in the context of upcoming emissions legislation such as Euro 7/VII, where N_2O could possibly be regulated.
- Most of the fuels tested have the potential to be renewable, with WTT benefits as well as the TTW effects studied, but in many cases additional OEM certification would be required to deploy such fuels for general use in the European market.

References

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   Concawe: https://www.concawe.eu/publication/fuel-effects-on-regulated-and-unregulated-emissions-from-three-light-duty-euro-5-and-euro-6-diesel-passenger-cars-2/
   SAE Mobilus: https://doi.org/10.4271/2020-01-2147
2. Williams, R., Pettinen, R., Ziman, P., Kar, K. and Dauphin, R. (2021). 'Fuel Effects on Regulated and Unregulated Emissions from Two Commercial Euro V and Euro VI Road Transport Vehicles'. In *Sustainability*, Vol. 13, No. 14:7985. This article, published in a special issue of *Sustainability* on 'Emissions from road transportation and vehicle management', presents the results of the commercial vehicles study. It can be downloaded free of charge from the Concawe or MDPI websites at the links below:
   Concawe: https://www.concawe.eu/publication/fuel-effects-on-regulated-and-unregulated-emissions-from-two-commercial-euro-v-and-euro-vi-road-transport-vehicles
   MDPI: https://doi.org/10.3390/su13147985
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Technological, operational and energy pathways for maritime transport to reduce emissions towards 2050

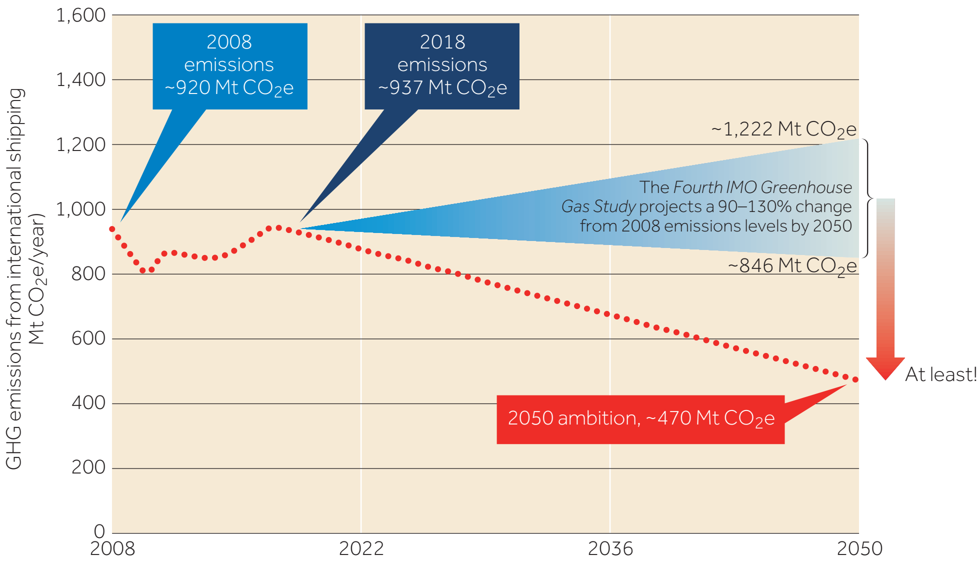
A recent study undertaken by Ricardo on behalf of the Oil and Gas Climate Initiative (OGCI) and Concawe identified various combinations of alternative fuels and technologies that could provide possible pathways for meeting the IMO's ambition for 2050. This article provides a summary of the outcomes of the study. A link to the complete study report is provided at the end of the article.

Author
Damien Valdenaire (Concawe)

Introduction

The International Maritime Organization's (IMO's) fourth greenhouse gas (GHG) study, published in 2020, gave its forecasts for the future development of emissions from international maritime transport (see Figure 1), based on long-term global economic scenarios consistent with limiting the global temperature rise to less than 2°C. These projections emphasised the considerable challenges that the industry faces in meeting the 2050 ambition.

Figure 1: Carbon dioxide equivalent (CO_2e) emissions from international shipping from 2008 to 2018, and projections to 2050 under scenarios consistent with a 2°C global temperature rise



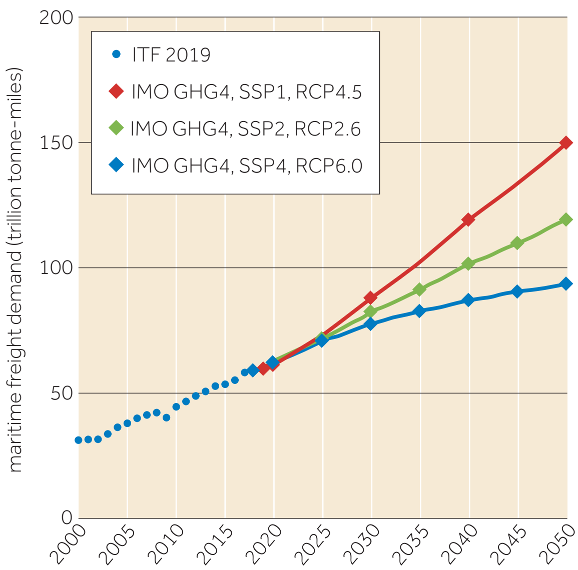
Historically, seaborne trade has been closely correlated with world gross domestic product (GDP), at least since 1990. World seaborne trade grows approximately in line with world GDP and has more than doubled over the past 20 to 25 years. Therefore, with anticipated growth in global GDP, there is a need to decouple international shipping emissions from economic growth.

The rapid growth in demand over the past 20 years has led to significant changes in the structure of the fleet, with increases in the size of new ships to leverage economies of scale. This has been largely driven by the requirements to reduce fuel costs, as these costs are one of the strongest incentives for operators. This has been particularly evident in the container sector, which has also been supported by a trend of increased containerisation of goods for transport, a trend that is expected to continue.

Because of the structure of the shipping sector, the introduction of new technologies is more difficult, because of the 'split incentive' issue, than in other transport sectors. This is because responsibilities such as fuel charges, operational measures, technological investments and cargo loading can be allocated to either ship owners or ship charterers. Whether or not there is an incentive for a ship owner to implement energy efficiency measures is often highly dependent on the charter rate that the charterer pays to the ship owner. If the benefit of the energy efficiency measure is not accrued by the party paying for its implementation, this can act as a barrier to the adoption of the measure when ordering a new ship.

Analyses of different sources of data have shown that global CO_2 emissions from international shipping were about 860 million tonnes in 2019, with a growth rate of more than 2% per annum from 2013 to 2018. The three main ship categories for CO_2 emissions were bulk carriers, container ships and tankers. Projections of future demand growth from different sources show considerable variations, ranging from 58% to 153% growth by 2050 (relative to 2018). The different future growth scenarios analysed for this study are shown in Figure 2.

Figure 2: Future growth scenarios for maritime freight demand



Notes:

Data sources: International Transport Forum (ITF) *Transport Outlook* (2019) and IMO's *Fourth IMO Greenhouse Gas Study* (2020).

GHG4 = *Fourth IMO Greenhouse Gas Study*

SSP = Shared Socio-economic Pathways — alternative plausible trajectories for societal development

RCP = Representative Concentration Pathways — GHG concentration trajectories adopted by the Intergovernmental Panel on Climate Change (IPCC)

Many operators have implemented reduced vessel speeds to reduce fuel consumption, emissions and costs. Speed reductions are especially effective in reducing fuel consumption when waiting times at ports are converted to a slower cruising speed (just-in-time arrival) and the cargo carrying capacity of vessels is maximised. Speed reductions of up to 30% have been used, though not for time-sensitive cargos. The use of reduced vessel speeds also requires more ships to be at sea to achieve the same delivery rates, reducing the overall effectiveness of the measure. Nonetheless, it is seen as having overall benefits, which will increase further as new ships are delivered with lower design speeds.

Analyses of ship demolition ages show that, for most categories, the average retirement age is about 25 years, while for roll-on/roll-off (Ro-Ro) ships it is about 35 years. These long lifetimes limit the rate of penetration of new technologies into the operating fleet, and developments such as lower design speeds can take several years to have an effect on the overall fleet efficiency. Some technologies, such as waste heat recovery have the potential to be retrofitted to the in-service fleet, thus accelerating the penetration of such technologies. However, these technologies tend to have a smaller impact on the overall fuel efficiency than other technologies that need to be incorporated at the design stage.

Meeting the IMO's 2050 decarbonisation ambition will need significant change in the shipping industry

The *Fourth IMO Greenhouse Gas Study*, published in 2020, indicated that significant progress has been made, with global emissions in 2018 being almost the same as those in 2008. However, the IMO's future projections of emissions from the sector in 2050 — between 90% and 130% of 2008 levels — miss the 2050 ambition by a considerable margin. To achieve the IMO's ambition will require the introduction and large-scale deployment of new technologies and/or alternative low-carbon fuels across international shipping.

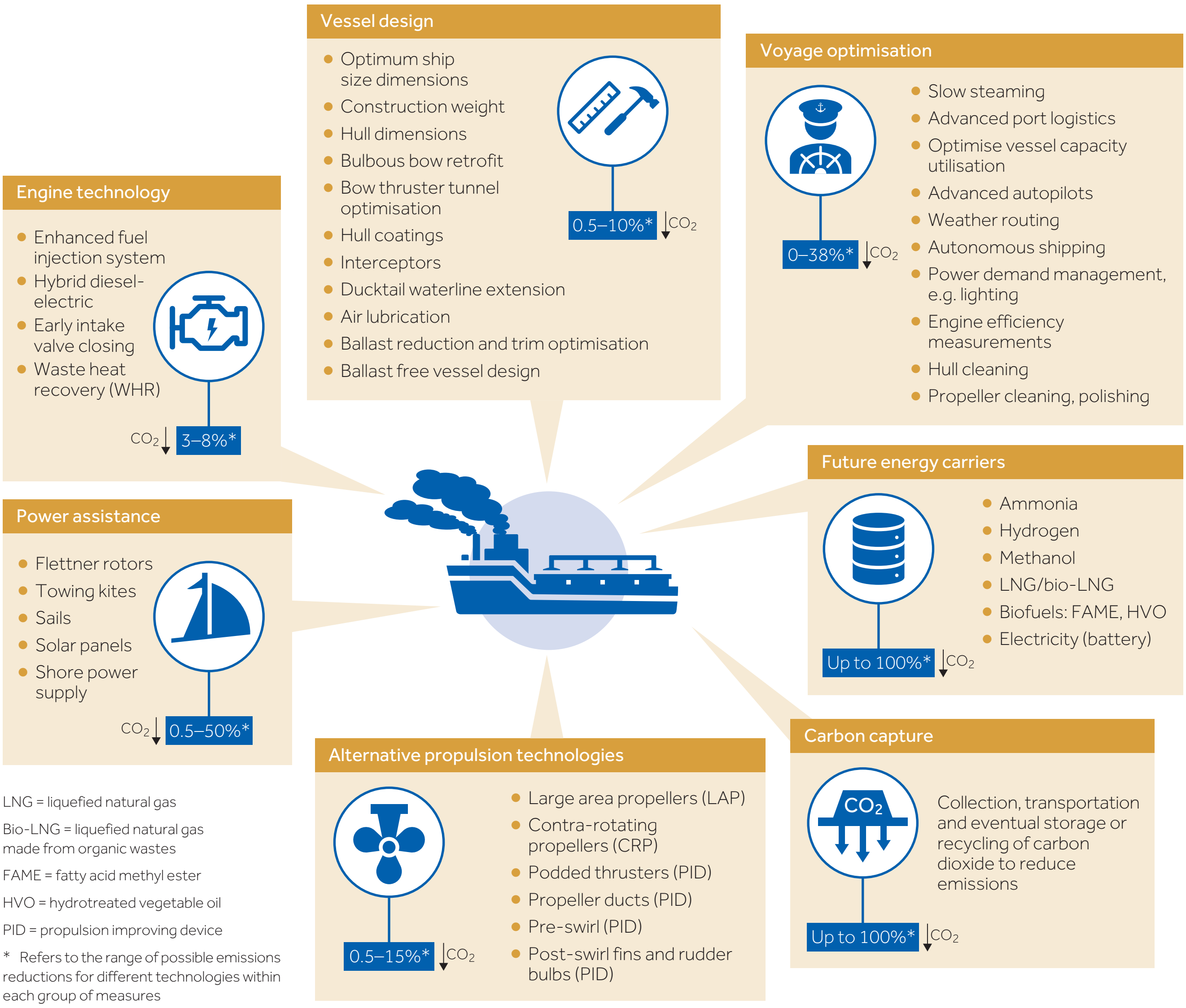
Traditionally, the demand for maritime transport has been well correlated with global GDP. Although projections for future development show changes in the nature of goods transported — largely due to decarbonisation efforts in other sectors, leading to a reduction in demand for transporting oil and coal but a commensurate increase in demand for transporting raw materials and products — the majority of projections continue to show a strong growth in demand.

Alternative fuels and technologies required to decarbonise international shipping

The study reviewed the available literature and interviewed multiple stakeholders to identify the technologies and alternative fuels that would be available to decarbonise international shipping. The different technologies and fuels are shown in Figure 3.

Each of the technologies considered was assessed for its applicability (ship categories), availability (entry-into-service dates), carbon reduction potential and cost (capital and operating).

Figure 3: Options to decarbonise shipping — alternative fuels and technologies



LNG = liquefied natural gas

Bio-LNG = liquefied natural gas made from organic wastes

FAME = fatty acid methyl ester

HVO = hydrotreated vegetable oil

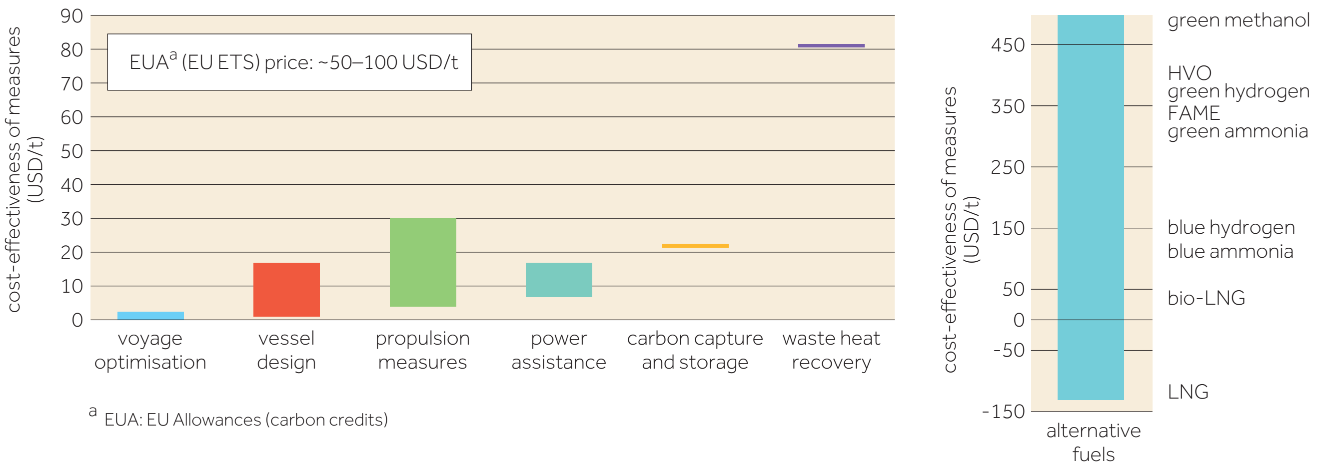
PID = propulsion improving device

* Refers to the range of possible emissions reductions for different technologies within each group of measures

Identification of the most cost-effective fuels and technology measures

A number of alternative fuels and technology measures were identified which have a wide range of cost-effectiveness, mostly below today's current EU ETS[1] prices. These are summarised in Figure 4.

Figure 4: Cost-effectiveness of the various technologies and alternative fuels considered



Three 'fuels and technology options' packages

Three different combinations of alternative fuels and technology options were defined as 'packages' depicting possible pathways for achieving the IMO's ambition. Each package was subsequently analysed to determine its potential impacts. The packages were not defined as the 'most likely pathways', but more to exemplify possible pathways, with significant variations to illustrate the range of routes available towards decarbonisation. These packages were characterised as shown in Figure 5.

Figure 5: The three 'fuels and technologies packages' defined for analysis in the study

Package 1	Package 2	Package 3
Characterised by an early pursuit of carbon-free alternative fuels	A moderate uptake of an interim alternative fuel (represented by LNG) in the short term	Maximum use of decarbonisation measures while using conventional fuels
Introduction of new-build ships using grey hydrogen and grey ammonia, and battery electric (coastal shipping) from 2025. Followed by a transition from grey to blue fuel pathways and to green from 2035 onwards.	From 2025, HFO and MDO use is assumed to be increasingly substituted with drop-in biofuels (FAME, HVO). LNG transitions to bio-methane (bio-LNG) from 2030 onwards.	Conventional fuels, HFO and MDO, with a later transition to reduced-carbon alternative fuels using pathways that provide some reductions in emissions. Gradual transition to use of bio-LNG, green methanol and green ammonia.
Medium take-up of energy efficiency technologies and operational measures. A 10% speed reduction is assumed for slow steaming. No on-board CCS.	Medium take-up of energy efficiency technologies and operational measures. A 20% speed reduction is assumed for slow steaming. No on-board CCS.	High take-up of energy efficiency technologies and operational measures. A 30% speed reduction is assumed for slow steaming. On-board CCS post 2030.

[a] HFO = heavy fuel oil [b] MDO = marine diesel oil [c] CCS = carbon capture and storage

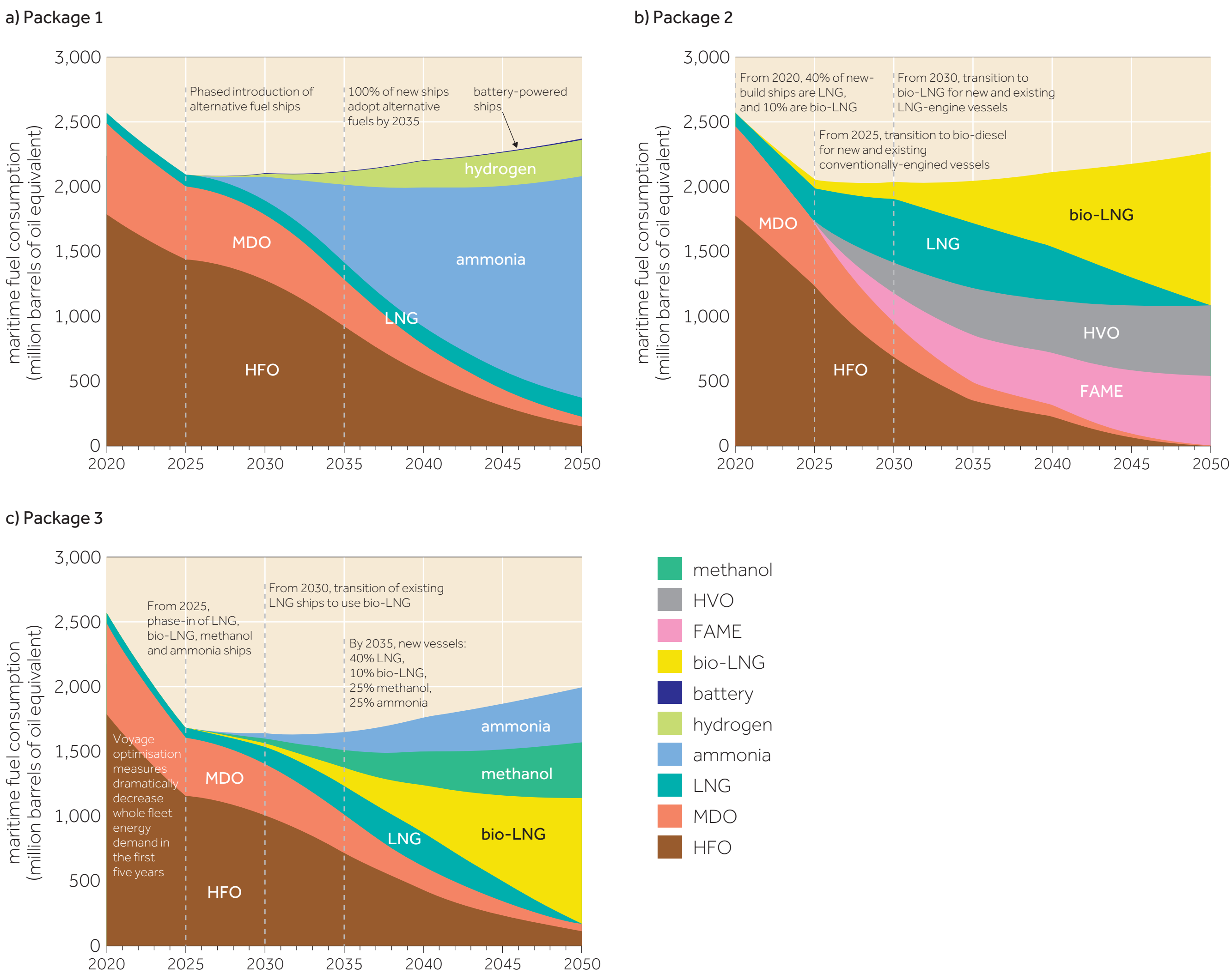
[1] European Union Emissions Trading System

The overall analysis presented in this study is based on a scenario model, investigating the potential emissions to 2050 under the three scenarios, together with the potential reductions in those emissions arising from the implementation of the sets of technologies and alternative fuels identified. It is important to recognise that these scenarios do not indicate the 'most likely' future, nor do they provide definitive indications of the costs to achieve particular levels of emissions savings, but indicate what can be achieved under certain assumptions.

Fuel consumption for the three packages up to 2050

The modelled fuel consumption for each of the three 'fuels and technologies' packages described above is shown in Figure 6.

Figure 6: Modelled fuel consumption to 2050 for each of the three packages defined in the study



The IMO's ambition is estimated to be met by all three packages when emissions are calculated on a well-to-wake basis

The results of the modelling showed that, by 2050, the emissions under the baseline scenario would be between 4% and 82% higher than in 2008, depending on the demand scenario assumed, compared to the IMO's ambition of a 50% reduction (also relative to 2008). These increases in emissions were calculated on a 'well-to-wake' basis, as this represents the full impact on the global climate and is important when considering the impact of alternative fuels.

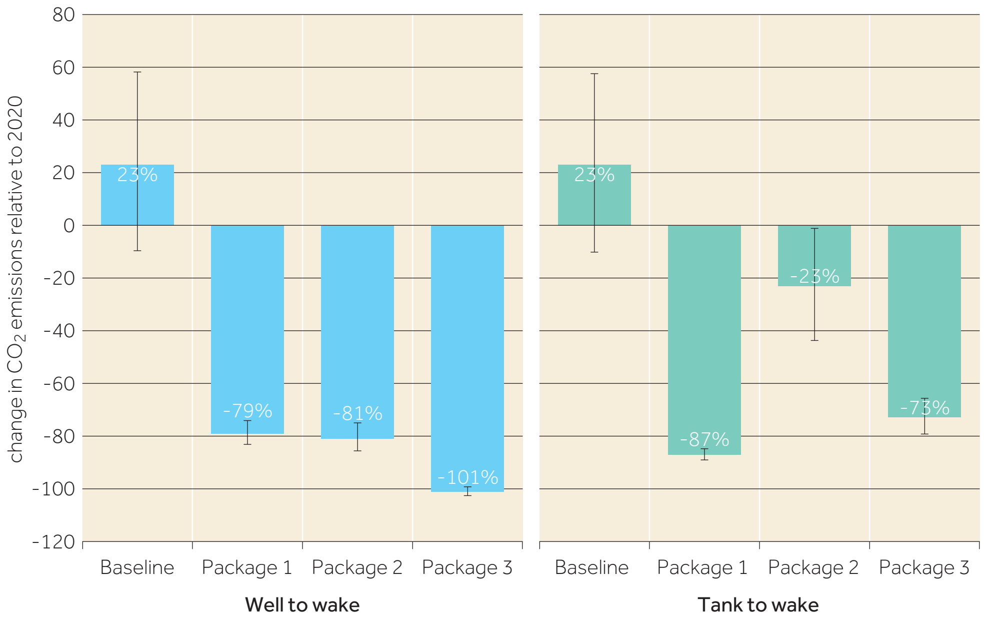
Under the three fuel and technology packages, these increased emissions (in the baseline scenario) are replaced by significant decreases in most cases by 2050:

- Under package 1, emissions are reduced by more than 70% relative to 2008 under all three demand scenarios, comfortably exceeding the IMO's ambition.
- Under package 2, the reductions in emissions are very similar to those under package 1.
- Under package 3, the reductions in emissions relative to 2008 reach approximately 100% under all three demand scenarios. The package includes a transition to 'green', but carbon-containing, fuels and the use of on-board carbon capture technology. The combination leads to a net capture of CO_2 over the complete fuel production and combustion process, leading to a net negative emission and a reduction of slightly more than 100%. Carbon capture is therefore assumed to be available in time for this scale of deployment; under the assumptions used in the modelling, for the central scenario, by 2050, approximately 35% of the global fleet is equipped with carbon capture technology. Carbon capture then contributes approximately 16% of the total well-to-wake emissions reductions under this package.

These changes in CO_2-equivalent (CO_2e) emissions are shown in more detail for 2050 (relative to 2020) in Figure 7 on page 25. Results are shown for both well-to-wake and tank-to-wake emissions, with the results for the central demand scenario shown as coloured bars and the range between the low and high demand scenarios represented by the error bars.

All three packages are estimated to exceed the IMO ambition on maritime decarbonisation by 2050, but this is only assured if the emissions are considered on a well-to-wake basis. Consideration may need to be given to reformulating the IMO's ambition on a well-to-wake basis and incorporating well-to-wake emissions in policy measures to capture the decarbonisation benefits of such alternative fuels and to enable their deployment.

Figure 7: Changes in CO_2e emissions in 2050 (relative to 2020) for all three packages under the central demand scenario (error bars indicate the range between the low and high demand scenarios)



Under package 3, about 16% of the total reduction in emissions to 2050 (relative to the baseline) is due to the use of on-board carbon capture. The relative contributions of vessel technologies, alternative fuels and carbon capture to the emissions reductions achieved under the three packages are shown in Table 1.

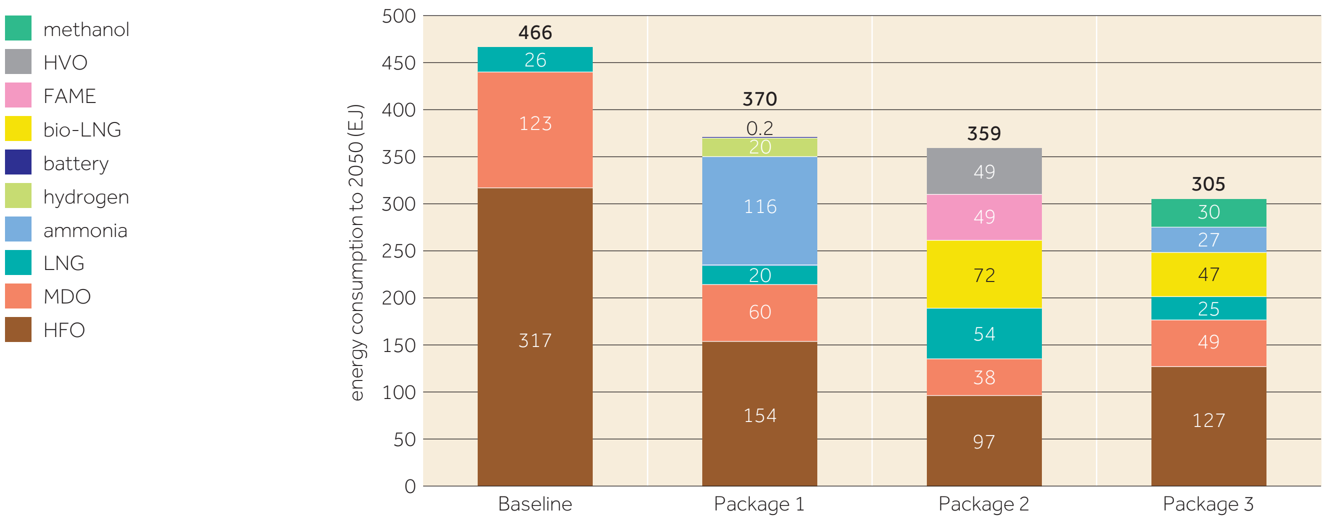
Table 1: The relative contributions of vessel technologies, alternative fuels and carbon capture to the emissions reductions achieved under the three packages

	Package 1	**Package 2**	**Package 3**
Technology	31%	34%	44%
Fuel	69%	66%	40%
Carbon capture	-	-	16%

The reductions in CO_2e emissions shown above are accompanied by improvements in carbon intensity (CO_2e emissions per unit work, expressed as g/tonne-mile) of between 50% (package 1) and 65% (packages 2 and 3) in 2030, relative to 2008, and between 91% (packages 1 and 2) and 101% (package 3) in 2050. These changes in carbon intensity are similar across the three demand scenarios.

The cumulative quantities of the different fuels required to 2050 under the three packages to achieve the emissions reductions described are shown in Figure 8.

Figure 8: Quantities of fuels required to 2050 to achieve the emissions reductions described in the study



Net present value of the accumulated additional total costs for ships from 2020 to 2050

The cost analyses show that achievement of the emissions reductions will increase costs by 4% (package 1), 9% (package 2) and 3% (package 3) over the central baseline scenario, based on total costs to 2050 (using a 10% discount rate). The total additional costs incurred are a combination of vessel capital costs, fuel costs and other vessel operating costs.[2] The fuel price projections used in this study were provided by IHS Markit. The modelling also includes estimates for the additional fuel bunkering costs. Some insight into the additional fuel production infrastructure costs is provided in Section 8 of the full report; however, as the additional fuel production costs are expected to be amortised through higher fuel prices, they are not included separately in the results discussed here. These costs are calculated for each of the fuel and technology packages and the baseline; the impacts of the packages are then seen as the difference from the baseline.

[2] The additional vessel capital costs include the addition of specific technologies but do not change with fuel type. The fuel costs are based on specific pathways for the production — these were selected from a range of options identified as providing high levels of well-to-wake emissions reductions, but they are not necessarily the pathways that would be adopted most widely.

These costs are calculated as incurred over the full period from 2020 to 2050; net present values (NPVs) are then calculated using a range of discount rates. The results for the central demand scenario using a discount rate of 10% are shown in Table 2.

Table 2: Cost analysis for the baseline case and each of the three packages from 2020 to 2050 (discounted costs, USD billion)

	Vessel capital costs	Fuel costs	Other operating costs[a]	Total NPV
Baseline	52	1,638	3,848	5,539
Package 1	91	1,751	3,932	5,774
Package 2	86	2,002	3,939	6,027
Package 3	465	1,452	3,803	5,720

[a] Other operating costs include crew costs, stores costs, lubricant costs, maintenance costs, insurance costs and administration costs

For packages 1 and 2, the additional total costs over the baseline are dominated by the increased fuel costs, while for package 3 vessel capital costs dominate (as expected as it has the highest level of additional vessel technologies applied of the three packages). The high fuel costs under package 2 are primarily related to the use of drop-in fuels, principally bio-LNG, FAME and HVO.[3] The investigations under this study identified higher projected fuel prices to 2050 for these fuels than other types.

Combining the calculated emissions reductions and additional costs, with a discount rate of 10% applied to both emission savings and costs, gives the cost-effectiveness values in USD/tonne CO_2e, as shown in Table 3.

Table 3: Cost-effectiveness analysis for the three packages (discounted cost-effectiveness, USD/tonne CO_2e)

	Vessel capital costs	Fuel costs	Other operating costs	Total NPV
Package 1	12	35	26	73
Package 2	8	84	21	113
Package 3	88	-40	-10	39

[3] There is a higher level of uncertainty in the price projections for bio-LNG as IHS Markit did not provide projections for it consistent with those for the other fuels; therefore, additional information was used when deriving the projection for bio-LNG for this study. Further information on the fuel price assumptions, and their contribution to the overall cost calculations, is given in Sections 6.2.1 and 7.3 of the full report.

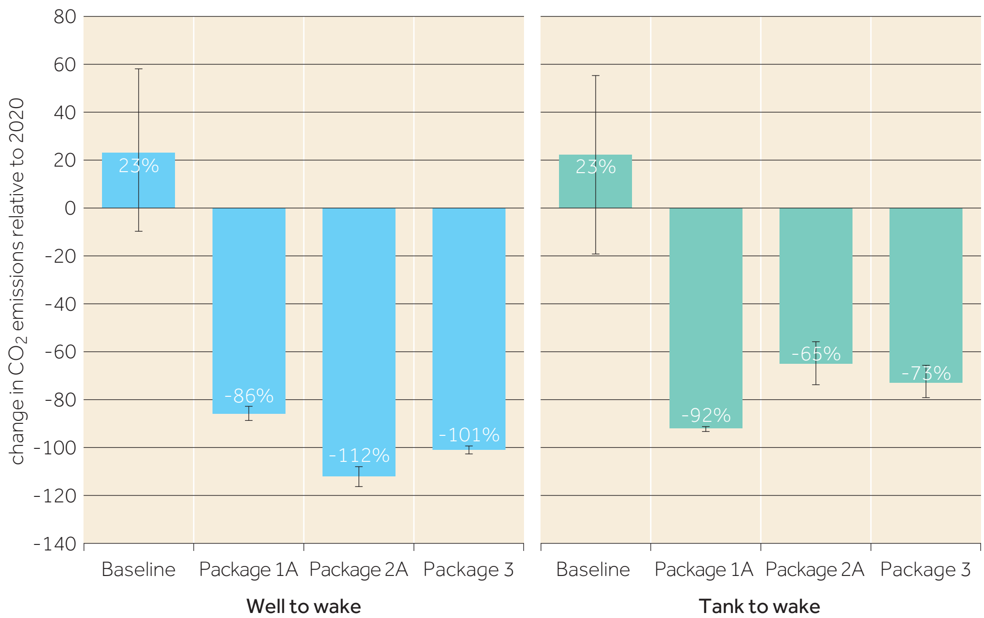
Package 3 has a slightly smaller cost increase over the baseline than package 1, and has significantly greater emissions savings, leading to a lower cost per tonne of CO_2.

The results of the emissions analyses indicate that the IMO's ambition can be met (and, indeed, surpassed) with a high confidence under the assumptions described — that is to say that if the fuels are switched as described, there is high confidence in the emissions that result from using these fuels; naturally, however, there is a lower level of confidence in the calculated costs. In addition to the uncertainty inherent in the fuel price projections, the actual costs will be sensitive to decisions made in the future (for example, a high uptake of one alternative fuel type could lead to prices for different fuel types that are significantly different from those assumed for this study, which were based on projections assuming a more balanced marketplace).

Sensitivity analysis based on increased deployment of vessel technologies

In addition to packages 1, 2 and 3 described previously, the alternative fuels assumptions of packages 1 and 2 were combined with the advanced technology assumptions of package 3, forming packages 1A and 2A, respectively. A sensitivity analysis was then undertaken to study the effect of the increased deployment of vessel technologies. Increasing the deployment of vessel technologies (relative to packages 1 and 2) gives increased emissions reductions, so that packages 1A, 2A and 3 all meet the IMO's ambition on both a tank-to-wake and a well-to-wake basis. These reductions in 2050, relative to 2020, are shown in Figure 9.

Figure 9: Changes in CO_2e emissions in 2050 (relative to 2020) for packages 1A, 2A and 3 under the central demand scenario (error bars indicate the range between the low and high demand scenarios)



The inclusion of the additional vessel technologies in packages 1A and 2A (compared to packages 1 and 2) reduces the energy demand and hence the fuel costs. Under package 1A, this reduction in fuel costs is greater than the increase in vessel costs associated with the additional technologies, leading to overall costs that are significantly lower than under package 1. Under package 2A, however, the increased vessel costs are almost equal to the reduction in fuel costs, leading to a small reduction in total costs compared to package 2. These results assume a 10% discount rate.

Table 4 shows the overall cost-effectiveness (USD per tonne of CO_2 abated) of the three packages studied under the main analysis (packages 1, 2 and 3), and the two additional packages formed to undertake the sensitivity analysis (packages 1A and 2A).

Table 4: Overall cost-effectiveness of packages 1, 2 and 3 (main analysis) and packages 1A and 2A (sensitivity analysis)

	10% discount rate (USD)	5% discount rate (USD)
Package 1	73	120
Package 1A	11	47
Package 2	113	149
Package 2A	83	120
Package 3	39	83

Risks and barriers

This study and others show that it should be technologically possible to decarbonise the global shipping sector to the level of the IMO's ambition. However, despite the technical feasibility, we have not so far seen rapid decarbonisation at the rate and scale required, and barriers to decarbonising the shipping sector remain — see Figure 10.

Figure 10: Risks and barriers to decarbonising the shipping sector

GHG reduction potential

- Uncertainty between 'tank to wake' and 'well to wake', and in how 'well to wake' is defined.
- 20-year global warming potentials make LNG/bio-LNG less palatable.

Price differential

- HFO price and scale is difficult to match.
- Regulatory intervention may help reach price parity.

Infrastructure

- Bunkering infrastructure and port refuelling facilities need to be scaled up.
- (Not a barrier for drop-in fuels.)

Production increase, location

- Alternative fuel production needs to be increased substantially and be appropriately located. (Dedicated new facilities? Or convert existing assets?)
- Renewable electricity sources may be in different geographies to existing assets.

Split incentives

- Customers and charterers not willing to pay for, or co-fund, lower-emission solutions.
- No clarity on how the preferred fuel(s) will be chosen to allow for scale.

Sustainability certainty

- Chemically identical brown/blue/green fuels need reliable certification schemes to provide assurance/guarantees.
- Uniform/standardised sustainability criteria may also need global consensus.

Conclusions

A range of fuel options are currently being assessed; multiple pathways involving different alternative fuels could meet the IMO's initial ambition for 2050. However, it remains to be seen whether the next edition of the IMO's '*Greenhouse Gas Study*' (due to be updated in 2023) will reflect a tightening of the IMO's current ambition level).

The IMO's ambition is estimated to be met by all three packages when emissions are calculated on a well-to-wake basis. However, only packages 1 (fuel switch: ammonia, hydrogen) and 3 (greater efficiency technology emphasis, CCS, bio-LNG, ammonia, methanol) would meet the ambition on a tank-to-wake basis.

Fuel costs are such a large component of total costs that energy efficiency measures to reduce fuel consumption are total cost savers (reduced spend on fuel; increased CAPEX spend on vessels; reduced impact on the fuel supply industry).

The 'drop-in' fuel package 2 (biofuel, bio-LNG), which faces fewer barriers to deployment, is estimated to be more expensive compared to the fuel switches in packages 1 and 3 that would require new vessel engine investments.

Long vessel lifetimes mean that emission pathways become locked in for longer (e.g. compared to road transport), hence it is important to act sooner rather than later to effect meaningful change.

The complete study report, entitled *Technological, Operational and Energy Pathways for Maritime Transport to Reduce Emissions Towards 2050*, can be downloaded from the Concawe website at:
https://www.concawe.eu/wp-content/uploads/Technological-Operational-and-Energy-Pathways-for-Maritime-Transport-to-Reduce-Emissions-Towards-2050.pdf

How additional actions in the road transport sector could improve air quality in Europe — an extension of the Concawe urban air quality studies

A modelling study has been undertaken to provide insight in potential additional actions that may be considered to improve compliance with air quality limit values in the future. The study was based on a scenario sensitivity analysis, focusing primarily on road transport emissions but also taking into account emissions from other sectors to provide context. This article summarises the results of the study.

Author

Athanasios Megaritis

Introduction

Over the years, emission reduction measures have resulted in significant improvements in overall air quality in Europe. However, air quality continues to be an issue of policy and public concern at European, national and city levels, as non-compliance with air quality limit values (AQLVs) still remains a challenge in many urban areas, especially for nitrogen dioxide (NO_2), particulate matter (PM) and ozone (O_3). Based on the latest official data, NO_2 and $PM_{2.5}$[1] concentrations were above the annual AQLV[2] at 8% and 4% of all measuring stations in Europe, respectively, while for O_3, more than 40% of all stations showed concentrations above the EU target value.[3] [1]

Road transport is considered a major source of air pollution, especially in urban areas, with 40% of total NO_x emissions in Europe being attributed to road transport emissions.[1] In addition, despite the fact that recent advances in PM treatment techniques have proven to significantly reduce the relative contribution of road transport to primary particulate matter emissions, road transport remains a contributor to PM concentrations, in particular with regard to $PM_{2.5}$. Targeting emissions from road transport is therefore considered to be one of the primary mechanisms for reducing urban concentrations of pollutants, with the more recent focus being on diesel passenger cars.

In response to this, the European Commission (EC) has traditionally utilised a number of regulatory initiatives to control the exhaust emissions of road transport, including setting increasingly stringent emissions standards for its fleet segment as well as introducing testing procedures which more closely reflect the actual vehicle emissions on the road. These initiatives have proven to be successful in reducing emissions of pollutants over the years. For example, NO_x and $PM_{2.5}$ emissions from road transport in Europe decreased by 50% and 60% respectively in 2018 compared to 2000 levels.[1] In addition, as the ongoing revision of the EU's Ambient Air Quality Directives aims to ensure close alignment of the EU AQLVs with the (lower) WHO air quality guideline values that have also been recently revised,[2] it is expected that there will be increased focus on the sources of these emissions, which are believed to be major contributors to non-compliance. The new draft regulatory proposals for the next iteration of vehicle emission standards (i.e. Euro 7/VII) that the EC has started to prepare is an example of this direction.

Concawe has recently undertaken two urban air quality studies[3,4] that aimed to better understand the contribution of road transport emissions to overall air quality in European urban areas, with a particular focus on the concerns over non-compliance with the annual AQLVs for NO_2 and PM. In the first study, the contribution of each element of the road transport fleet was explored. In the second study, the focus was largely on diesel passenger cars and concerns over the 'under-delivery' of legislated Euro 6 emission limits under real driving conditions.

[1] $PM_{2.5}$ = particulate matter with an aerodynamic diameter of less than 2.5 µm

[2] EU annual AQLVs: $PM_{2.5}$ = 25 µg/m^3, NO_2 = 40 µg/m^3

[3] EU target value: maximum daily 8-hour O_3 mean = 120 µg/m^3 (not to be exceeded on more than 25 days)

In particular, using modelling and the results of an earlier study that focused on determining the actual and expected real driving emissions for multiple classes of Euro 6 vehicles (Euro 6b, Euro 6c, Euro 6d temp, Euro 6d)[5] as input, Concawe assessed the impact that a fleet turnover to the latest Euro 6 diesel passenger cars would have on NO_2 and PM compliance during the period 2020–2030 throughout the EU-27 + UK. Several emissions scenarios were examined, including a scenario where all new passenger cars are replaced with zero-emission vehicles. The results show that, with a turnover of the vehicle fleet from older vehicles to new vehicles, the latest Euro 6d diesel vehicles will be as effective as zero-emission vehicles in helping cities become compliant with the AQLVs. In addition, the study showed that there is almost no difference in population exposure to NO_2 concentrations above the limit value when replacing the diesel passenger car fleet with zero-emission vehicles or with Euro 6d-compliant diesel passenger cars.

Building on the findings of Concawe's earlier UAQ studies, this study aims to give insights into the important policy question of what additional actions can be undertaken to significantly improve air quality in Europe. In this context, Concawe used the same methodology as that used in the analyses that underpinned each of the previous UAQ studies, and explored in more detail the effects of various rates of substitution of diesel-powered road transport vehicles (e.g. passenger cars, light-duty commercial vehicles and heavy-duty vehicles) with electric-powered vehicles undertaking the same level of activity. Although road transport emissions were the primary focus of the study, additional scenarios were explored which examined emissions reductions from other sectors so that the contribution of road transport to improving compliance could be considered in context with other sources. The study covered all of the EU-27 + UK with a detailed focus on the same 10 cities used in the earlier Concawe UAQ studies, namely Berlin, Bratislava, Brussels, London, Madrid, Milan, Munich, Paris, Vienna and Warsaw. For brevity, the article uses illustrative examples from the analysis to demonstrate the results of the study.

Modelling approach

The AQUIReS+ model[3] been used to forecast the effect of emissions changes on atmospheric concentrations of NO_2, $PM_{2.5}$ and O_3 at all monitoring stations across the EU included in the European Environment Agency's (EEA's) Air Quality e-Reporting dataset.[6] This ensures that the modelling is directly related to the individual measuring stations used to monitor compliance with the AQLVs. The model uses a gridded emission inventory and source-receptor relationships[7] that relate a change in emission to a change in concentration. These derive from regional chemical transport models (EMEP,[8] CHIMERE[9]) used in air quality studies. The local environment, traffic and topographical characteristics of each station are also taken into account by the model during the predictions. Model predictions for each monitoring station are also compared with measured data from the EEA's Air Quality e-Reporting dataset to ensure that the model performs well in reproducing concentrations of pollutants over historic years. A detailed overview of the model evaluation and a description of the data sources and dataflows in the model are presented in earlier studies.[3,10]

Emissions scenarios

Base case

A base case emissions scenario was used as a starting point in the modelling, aligned with the January 2015 Thematic Strategy on Air Pollution Report #16 (TSAP16) Working Party for the Environment (WPE) Current Legislation scenario.[11,12] This emissions dataset was developed for the EU Air Policy Review process[13] and was generated by IIASA's GAINS model.[14] The Current Legislation scenario is an official EU projection of how emissions (based on multiple sector contributions) will evolve over time, and takes account of economic growth and the progressive introduction of European legislation currently in force. Projections are made in five-year steps (i.e. 2015–2020–2025–2030). The geographic distribution of emissions is accounted for at a fine scale, and national emissions for the EU Member States (EU-27 + UK) are calculated by spatial aggregation.

The base case road transport emissions calculations utilised the TREMOVE 3.3.2 alternative dataset and the COPERT 4 v11.8.5 emissions factors. For the purposes of this study however, the road transport emissions in the base case emissions scenario were updated to take into account the findings from the earlier Concawe-Ricardo study.[5] Under the study, it is assumed that all Euro 6 diesel passenger cars introduced in a specific year are assumed to conform to the median level of the Concawe-Ricardo results (Table 1), while all new diesel passenger car registrations from 2020 onwards are assumed to be Euro 6d compliant.

Table 1: NO_x median conformity factors[4][4] for diesel passenger cars used in the base case emission scenario

	Euro 6b, pre-2015	Euro 6b, post-2015	Euro 6c	Euro 6d (temp)
Median NO_X	5.41	1.90	1.21	0.76[5]

[4] The conformity factor is a simple coefficient of the legislated limit value (LLV); for example, a conformity factor of 1.5 is one and a half times the LLV. This was introduced in Commission Regulation (EU) 2016/427 of 10 March 2016.

[5] In any scenario where the conformity factor was measured as being less than 1, the modelling has assumed a conformity factor of 1, which serves to ensure that the model reflects the minimum effect that full compliance with the legislated emissions limits would have on air quality.

Figures 1 and 2 (below) provide an overview of the projected EU emissions[6] of NO_x and $PM_{2.5}$ used in the base case. Each source sector is shown separately so that the contribution of each sector to overall emissions can be clearly seen. Over the 15-year period from 2015 to 2030, NO_x emissions are projected to decline by approximately 50% (Figure 1). Road transport emissions have seen the greatest reduction of all sectors, amounting to approximately 80% by 2030, while for 2025 and beyond it is forecast that the road transport sector will no longer be the primary contributing sector, with energy production and industrial combustion accounting for 23% and 25% of NO_x emissions, respectively. The road transport contribution to total EU NO_x emissions is projected to fall from 43% in 2015 to 18% by 2030.

$PM_{2.5}$ emissions also show a downward trend over the 15-year period, with a 20% reduction by 2030. The $PM_{2.5}$ contribution from road transport is projected to stabilise from 2020 onwards as the non-exhaust fraction dominates the overall emissions of PM. Residential combustion is by far the most significant source of $PM_{2.5}$ emissions in all years shown (more than 40% in all years).

Figure 1: Sectoral NO_x emissions for Europe under the base case

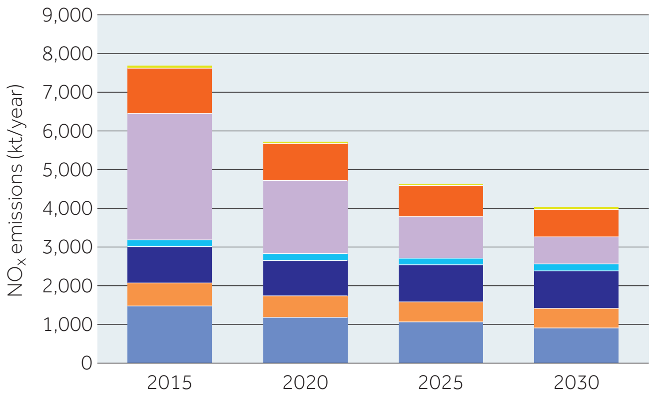
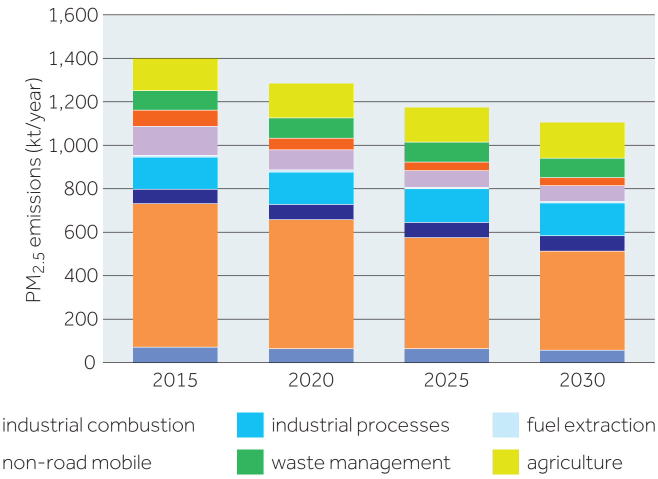


Figure 2: Sectoral $PM_{2.5}$ emissions for Europe under the base case



Source: IIASA TSAP #16/GAINS model, with updated road transport data based on the Concawe-Ricardo study[5]

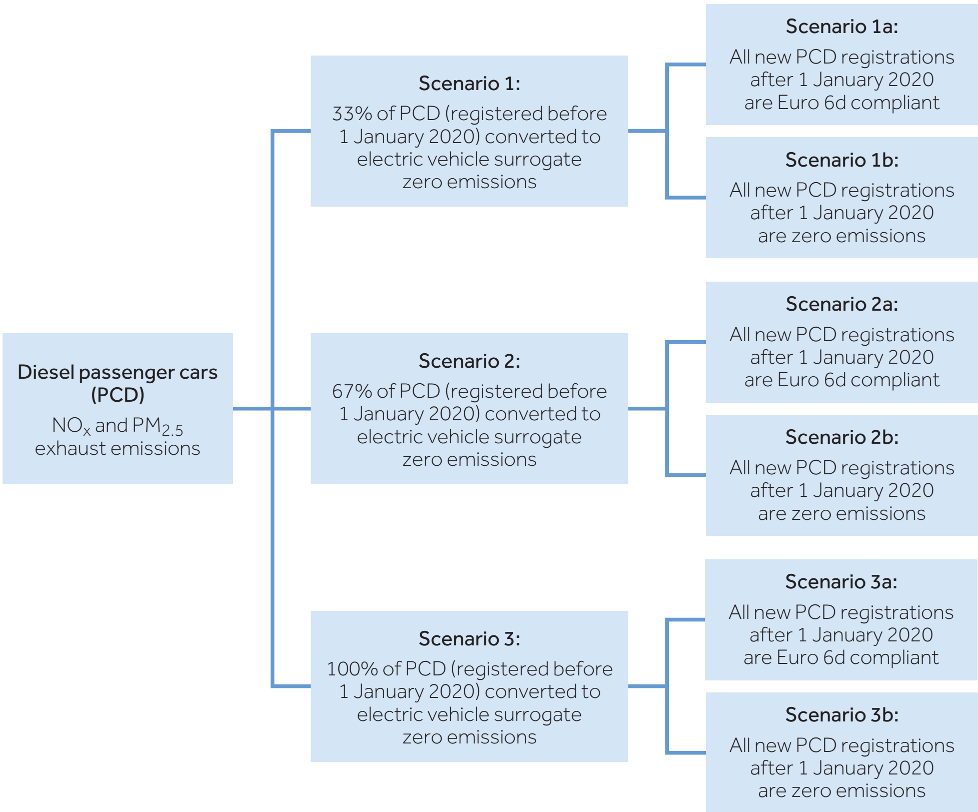
Road transport emissions scenarios

As road transport is the major focus of this study, the majority of the emissions scenarios explored targeted this sector and, in particular, the diesel-powered fleet segment. Nine different scenarios were designed that involved different rates of substitution of diesel-powered vehicles (i.e. passenger cars, light-duty commercial and heavy-duty vehicles) with electric-powered vehicles undertaking the same level of activity. The flow charts in Figures 3 to 5 on pages 35–37 describe the road transport scenarios examined under the study, and the graphs present the associated NO_x emissions considered in each scenario.

[6] The figures provide an indication of the trends and relative contributions of NO_x and $PM_{2.5}$ sectoral emissions, which is representative of all EU countries. The absolute values, however, are country-specific.

Figure 3: Diesel passenger car (PCD) scenarios examined in the study, and the associated NO_x emissions (note: emissions for Scenario 3b are zero)

a) Diesel passenger car scenarios



b) Diesel passenger car NO_x emissions

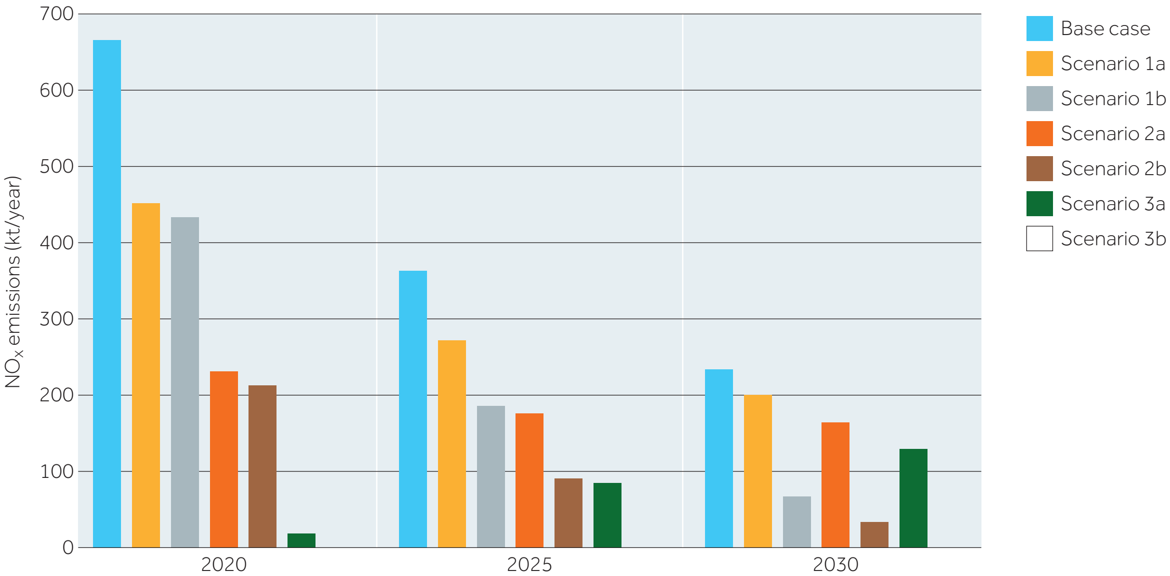
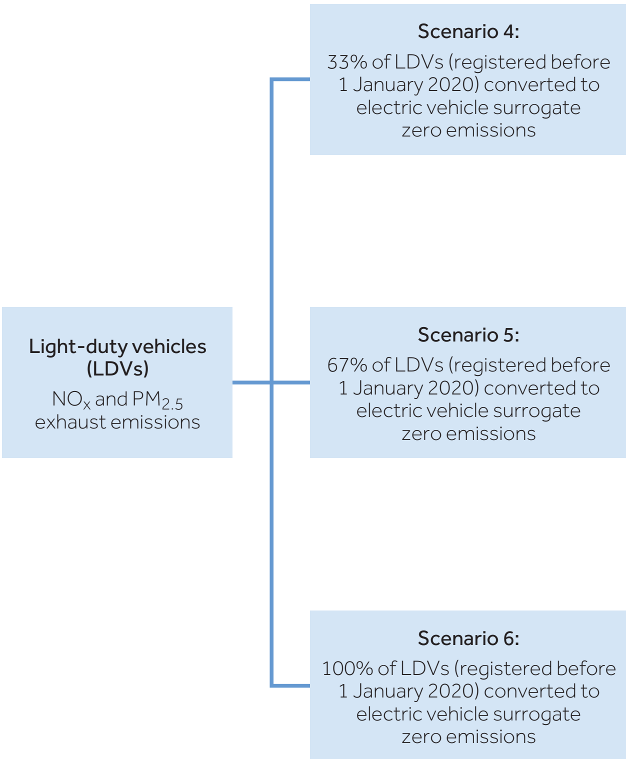


Figure 4: Light-duty vehicles (LDVs) scenarios examined in the study, and the associated NO_x emissions

a) Light-duty vehicle scenarios



b) Light-duty vehicle NO_x emissions

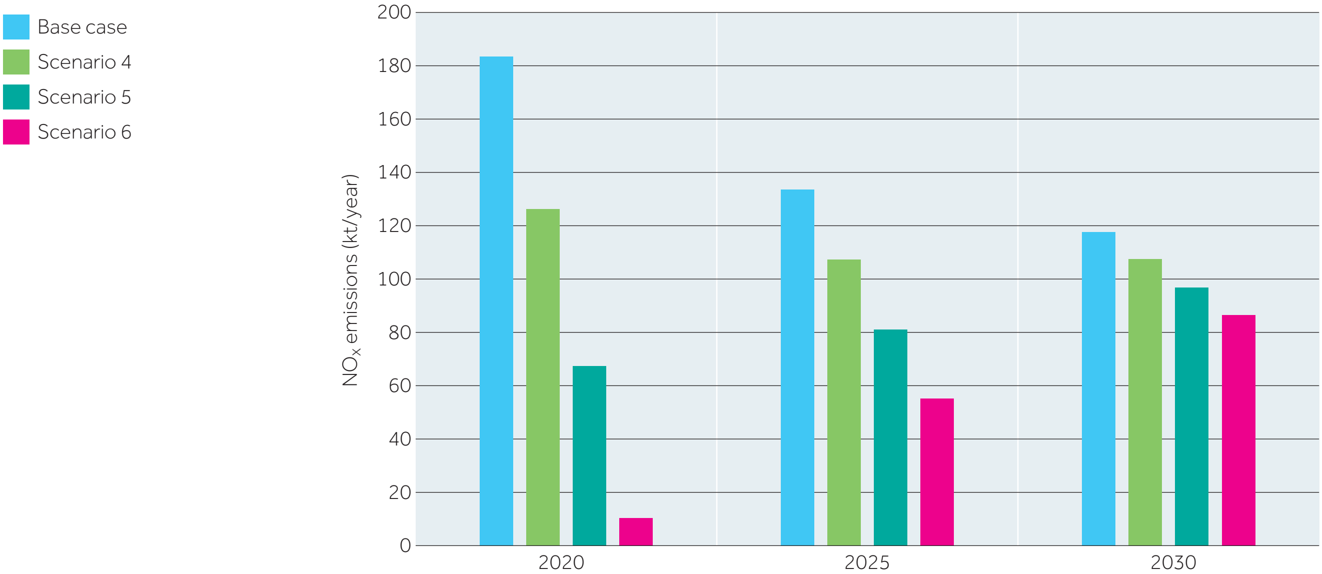
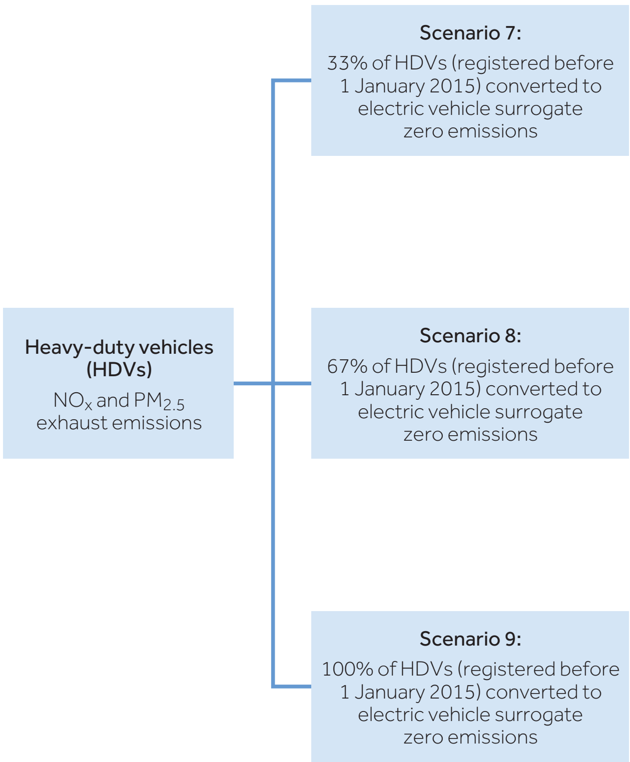
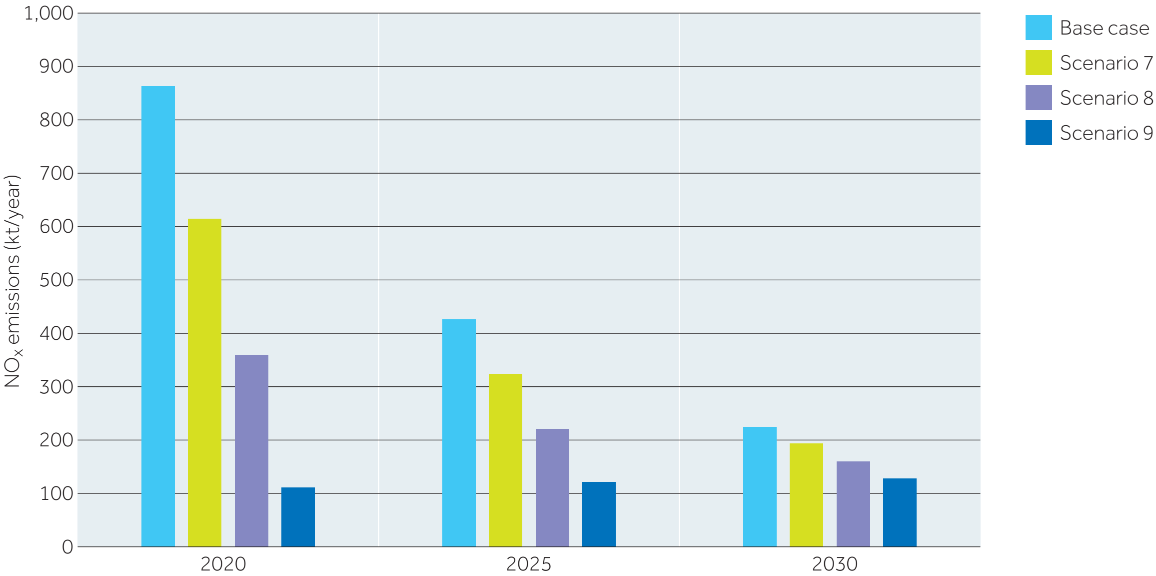


Figure 5: Heavy-duty vehicles (HDVs) and buses scenarios examined in the study, and the associated NO_x emissions

a) Heavy-duty vehicle and bus scenarios



b) Heavy-duty vehicle and bus NO_x emissions



Additional emissions scenarios evaluated

Additional emission reduction scenarios were examined in the study, to assess their further reduction potential as well as to put the contribution of road transport to compliance improvement in context. These scenarios involved measures/assumptions on emissions sources that are significant in urban areas (i.e. Scenarios 10, 11). Additionally, the study extended its focus in terms of the pollutants assessed, and included an assessment of O_3 compliance in urban areas. For this purpose, three additional scenarios were considered targeting VOCs emissions, an important precursor of O_3 formation. Table 2 provides a summary of the additional scenarios examined in this study.

Table 2: List of the additional scenarios examined in this study

Scenario	Description	Examined pollutant(s)
Scenario 10	Emissions as described in the base case but with maximum available NO_x and PM abatement technologies assumed for the domestic heating sector from 2025.	$NO_x/PM_{2.5}$
Scenario 11	Emissions as described in the base case but, from 2020, with substitution of base case solid fuel burning in the domestic sector with gas oil/natural gas.	$PM_{2.5}$
Scenario 12	Emissions as described in the base case but, from 2020, with road transport VOC emissions reduced to zero.	O_3
Scenario 13	Emissions as described in the base case but, from 2020, with road transport VOC emissions doubled.	O_3
Scenario 14	Emissions as described in the base case but, from 2020, with VOC emissions from the storage and distribution of gasoline reduced to zero.	O_3

Results

NO_2 compliance

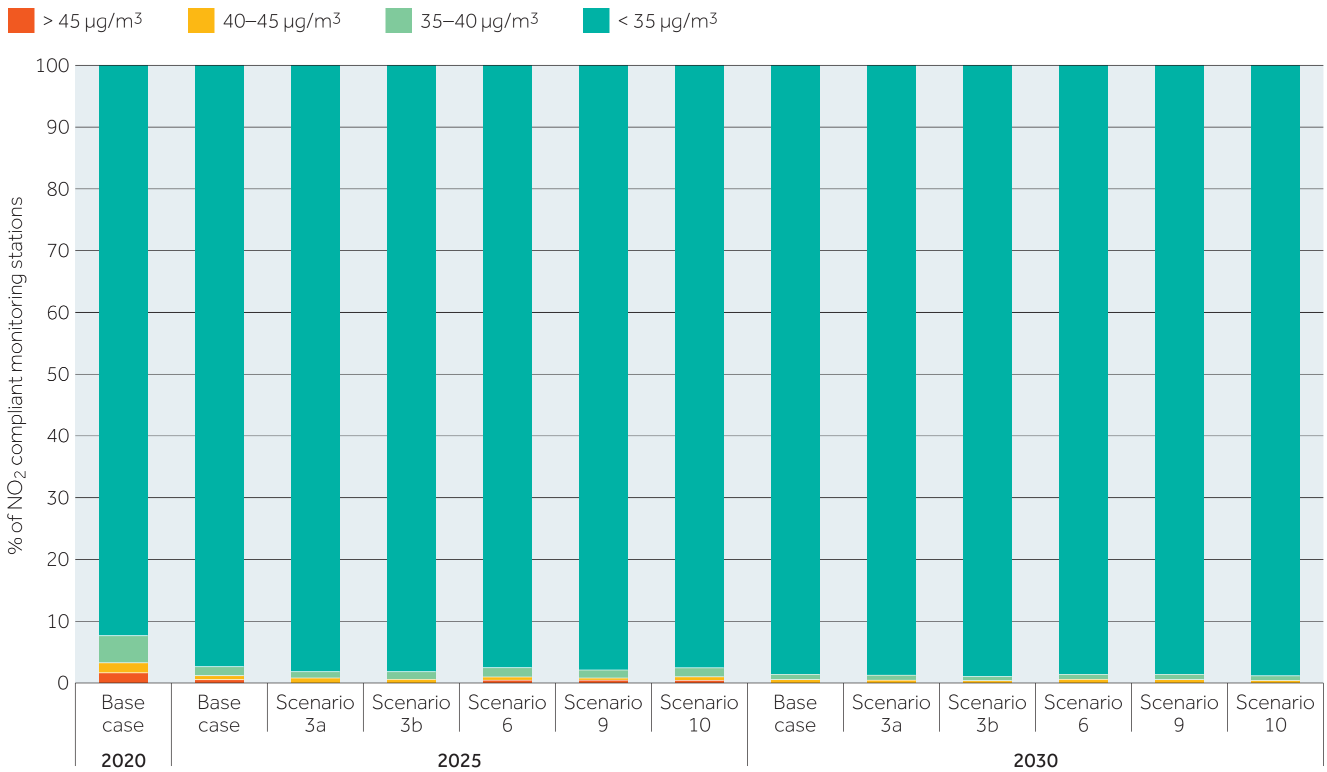
Figure 6 on page 39 shows how the modelled compliance of NO_2 monitoring stations[7] with the current EU AQLVs at a European level is projected from 2020 onwards until 2030 under the base case as well as under some of the emissions scenarios examined in this study.

A high degree of NO_2 compliance with the current AQLVs is already being achieved from 2020 across the EU under the base case scenario, with around 96% of the stations being compliant or probably compliant.[8]

[7] As the focus of the study is on air quality in urban areas, only stations located at urban and suburban areas were used in the analyses.

[8] To account for uncertainty in the model with respect to compliance with the given AQLV, a specific band of uncertainty has been assigned to each monitoring station (i.e. 5 µg/m^3).

Figure 6: NO_2 station compliance (2020–2030) in Europe under the base case and different scenarios examined (EU AQLV = 40 μg/m^3)

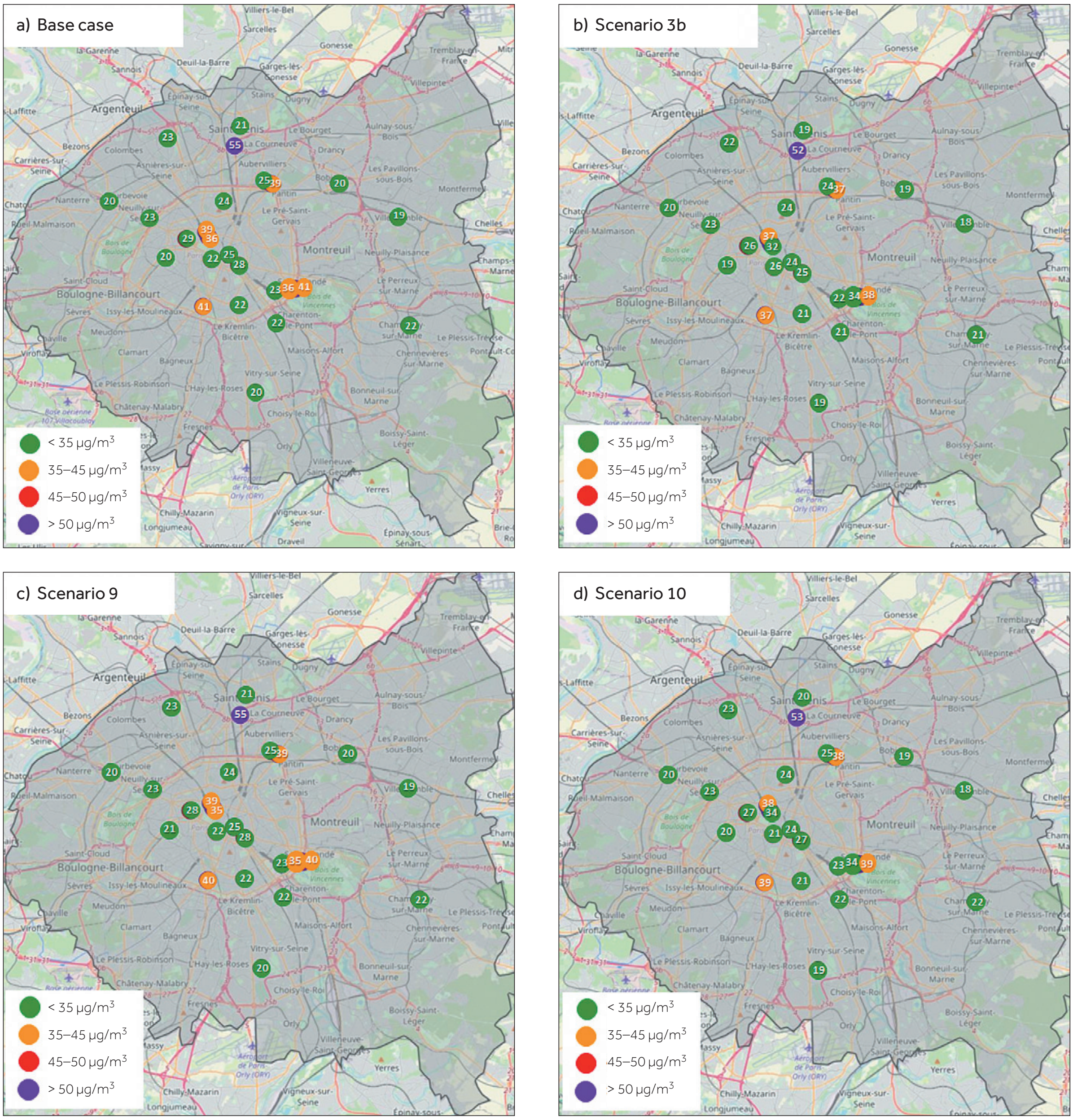


NO_2 compliance is projected to increase over the years, with almost 99% of the monitoring stations (urban/suburban) being compliant in the EU by 2030. The additional 'beyond the base case' scenarios are predicted to improve NO_2 compliance slightly, with measures targeting diesel passenger cars and heavy-duty vehicles being more effective (Scenarios 3a/b and 9 respectively). However, this slight improvement is rather limited and only achieved in the shorter term (i.e. 2020–2025), while post 2025 all additional road transport scenarios are predicted to have a limited further impact on the NO_2 compliance picture. In addition, the implementation of all available NO_x abatement technologies in the domestic heating sector (Scenario 10) is also predicted to have a negligible improvement in NO_2 compliance.

The analyses of the results at a national level indicate that, from 2025 onwards, NO_2 compliance with the current EU AQLV will no longer be an EU-wide issue, as the majority of the countries are predicted to achieve full compliance with the current NO_2 AQLV. Only a handful of stations (~15) remain non-compliant by 2030, with half of them located in France and the remainder in Germany, Italy and the UK.

A further city-focused analysis in these non-compliant countries shows that NO_2 non-compliance will be an issue in specific parts of major cities (e.g. Paris) (Figure 7a), regardless of the measures taken nationally. These findings highlight the importance of targeted city-specific measures, identified by a thorough source attribution analysis, rather than further national or European-wide measures. This is also evident from the limited impact of NO_2 compliance improvement that the 'beyond the base case' scenarios will offer in the long term.

Figure 7: NO_2 monitoring station compliance in Paris in 2030, under four different scenarios examined in the study



However, if the current EU NO_2 AQLV is lowered to align with the revised WHO air quality guideline value (i.e. 10 µg/m^3), it is predicted that non-compliance will not only affect specific cities but will become an EU-wide problem (Figure 8). By 2030, more than half of the stations located in urban areas will exceed (or probably exceed) the WHO air quality guideline value under the base case scenario, while significant non-compliance issues will still exist in all additional 'beyond the base case' transport scenarios examined here. This indicates both (a) the need for considering additional measures beyond the transport sector to further improve compliance, and (b) the fact that the alignment of the EU AQLV with the WHO air quality guideline value by 2030 will present considerable challenges.

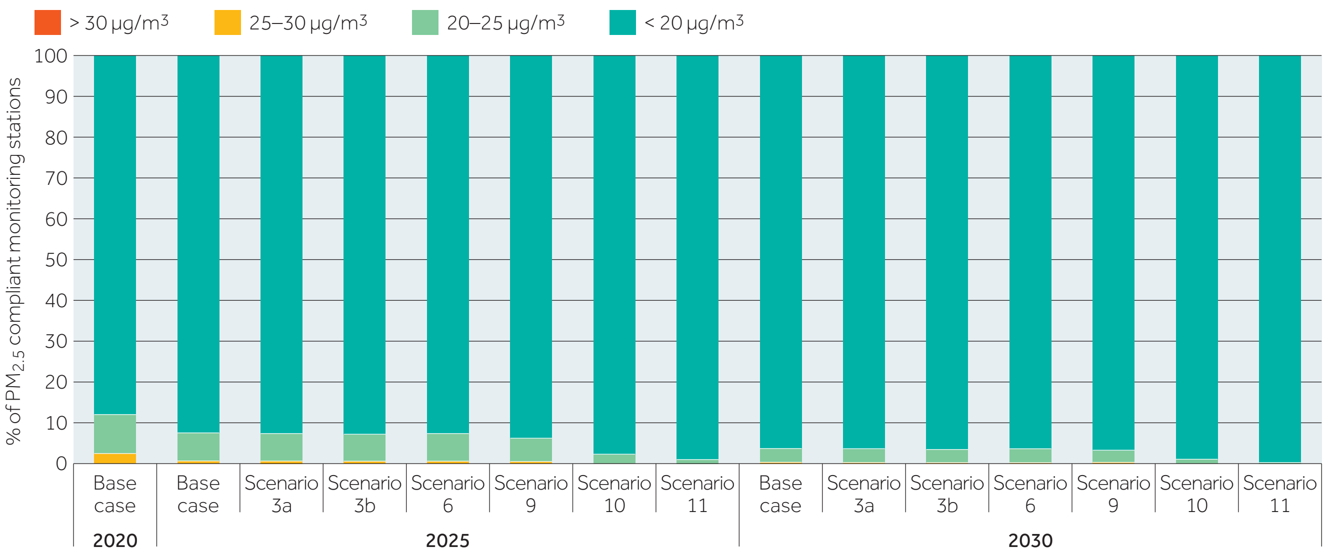
Figure 8: NO_2 station compliance (2020–2030) in Europe under the base case and different scenarios examined in the study
(WHO air quality guideline value = 10 µg/m^3)

$PM_{2.5}$ compliance

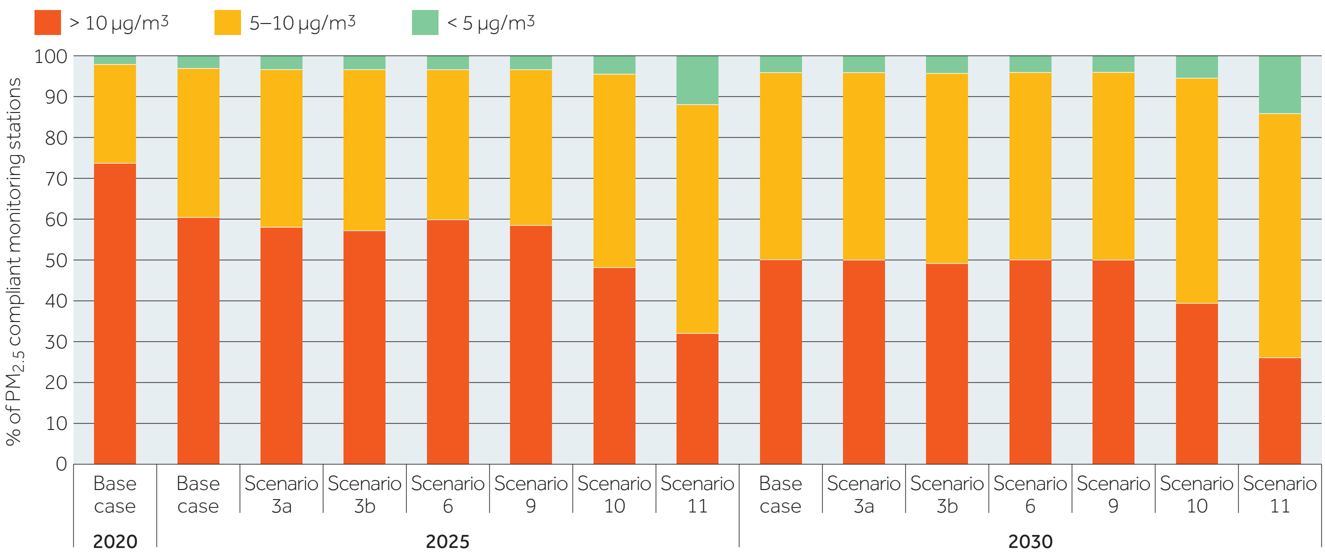
The already-legislated emission reduction measures are predicted to result in a high degree of $PM_{2.5}$ compliance with the current EU AQLV at monitoring stations in all EU Member States. By 2025, almost complete compliance is predicted for $PM_{2.5}$ across the EU, with approximately 92% of all $PM_{2.5}$ monitoring stations (urban/suburban) in Europe measuring $PM_{2.5}$ below 20 µg/m^3 and 7% of them registering $PM_{2.5}$ concentrations between 20–25 µg/m^3 (Figure 9).

Figure 9: $PM_{2.5}$ station compliance (2020–2030) in Europe under the base case and different scenarios examined

a) $PM_{2.5}$ compliance with the current EU AQLV (25 µg/m^3)



b) $PM_{2.5}$ compliance if the current EU AQLV is lowered to align with the WHO guideline value of 5 µg/m^3

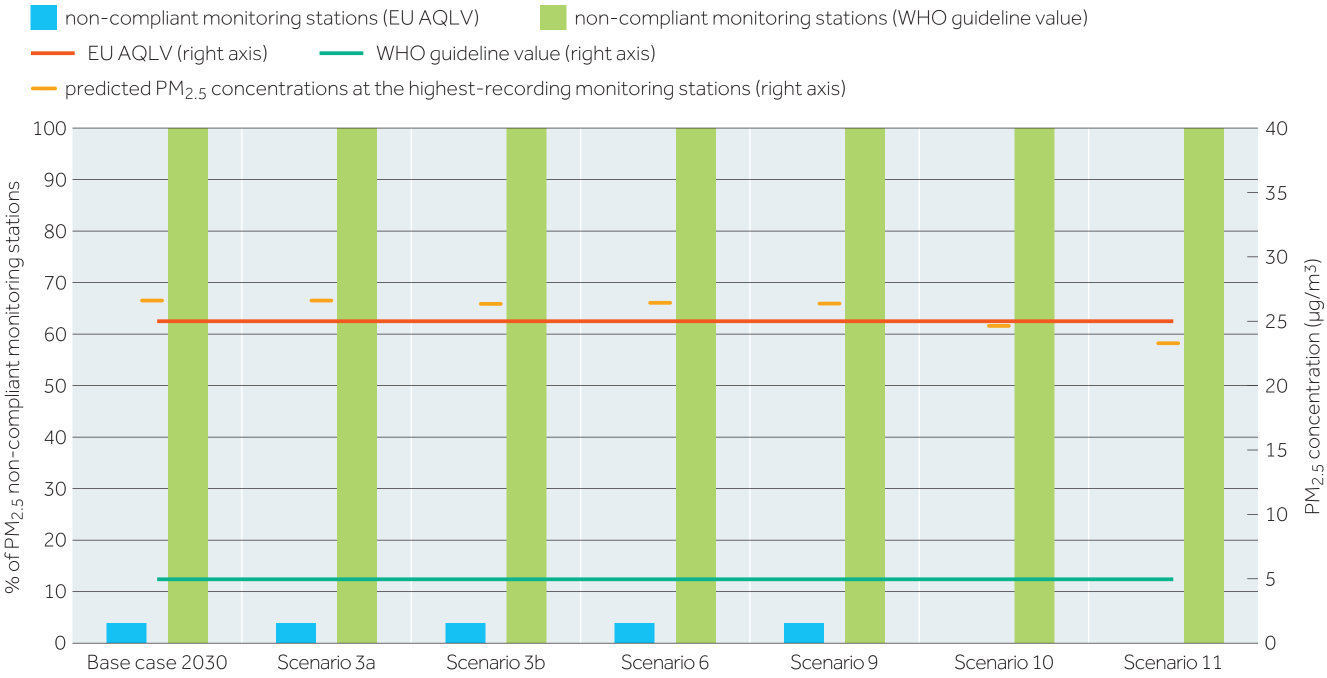


Of the scenarios considered, the results show that none of the 'beyond the base case scenarios' targeting road transport will offer any improvement in terms of $PM_{2.5}$ compliance beyond 2025, while their impact in the shorter term (between 2020 and 2025) will be limited, with most improvements resulting from the targeting of HDVs (Figure 9a). On the other hand, further emission controls or fuel substitution of solid fuel burning in the domestic sector are predicted to have a more significant impact on the residual $PM_{2.5}$ non-compliance.

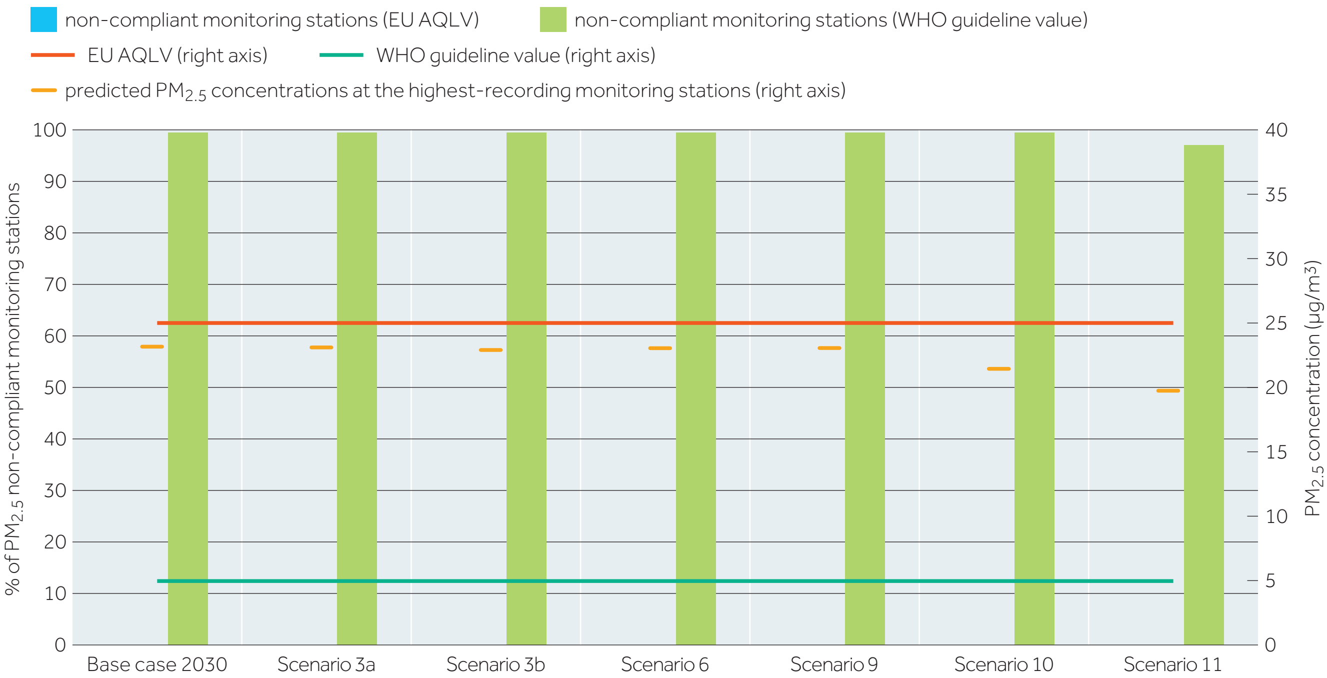
The $PM_{2.5}$ compliance picture in the EU changes significantly if the current EU AQLV for $PM_{2.5}$ is lowered to align with the WHO air quality guideline value (i.e. 5 µg/m^3), as this will impose significant and widespread non-compliance issues in the EU (Figure 9b). As expected, further road-transport measures only offer a negligible improvement in compliance with the WHO air quality guideline value, while in comparison, implementing measures to mitigate emissions from the domestic sector (Scenarios 10, 11) will greatly improve the number of monitoring stations compliant with the WHO air quality guideline value. However, even under these scenarios more than 80% of EU stations will still measure $PM_{2.5}$ above the limit value in 2030, and full compliance will not be achieved in the majority of EU Member States. This is clearly seen in the examples of Poland and Italy, where an alignment of the current EU AQLV with the WHO air quality guideline value will result in both countries — which are otherwise predicted to be fully compliant (Italy) or close to achieving full compliance (Poland) in 2030 — facing significant non-compliance issues (see Figure 10 on page 44). In particular, in Poland none of the scenarios examined in this study will result in $PM_{2.5}$ concentrations below the WHO air quality guideline value; this highlights the significant non-compliance challenge that Member States will face when a close alignment between the EU AQLVs and the WHO air quality guideline values is considered. These findings are consistent with an earlier Concawe study[15] which examined in detail the practicability of achieving compliance with the current EU AQLVs for $PM_{2.5}$ and NO_2, as well as lower limit values, under some potential emission reduction scenarios.

Figure 10: Predicted percentage of $PM_{2.5}$ non-compliant stations in Poland and Italy in 2030, under the different scenarios examined

a) Poland



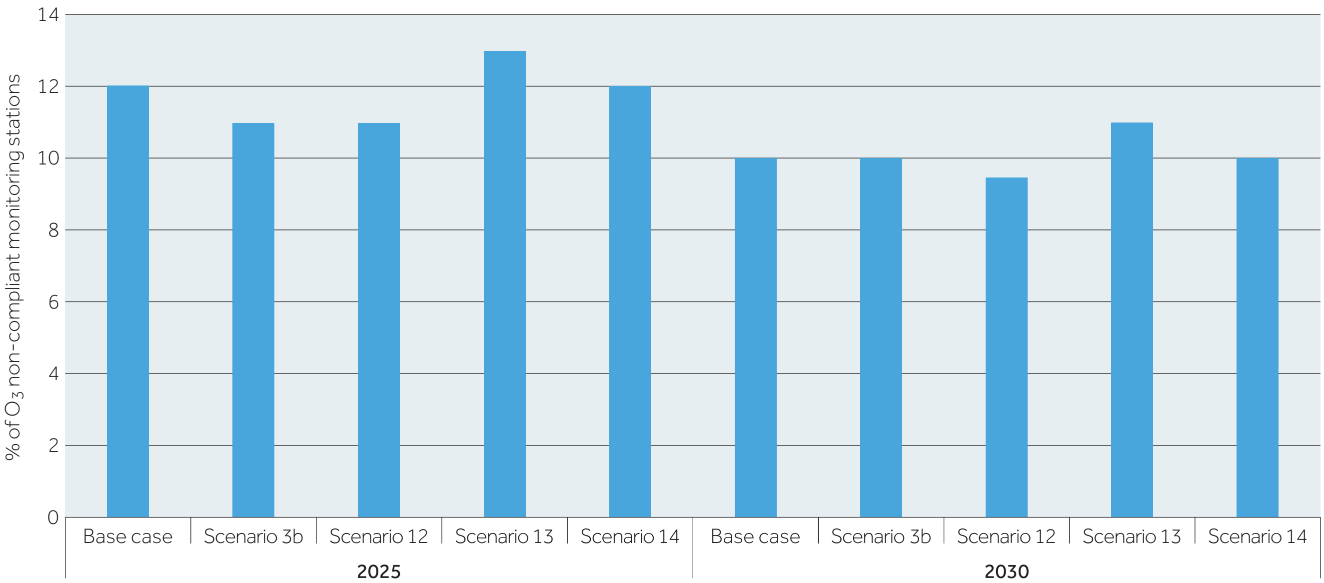
b) Italy



O_3 compliance

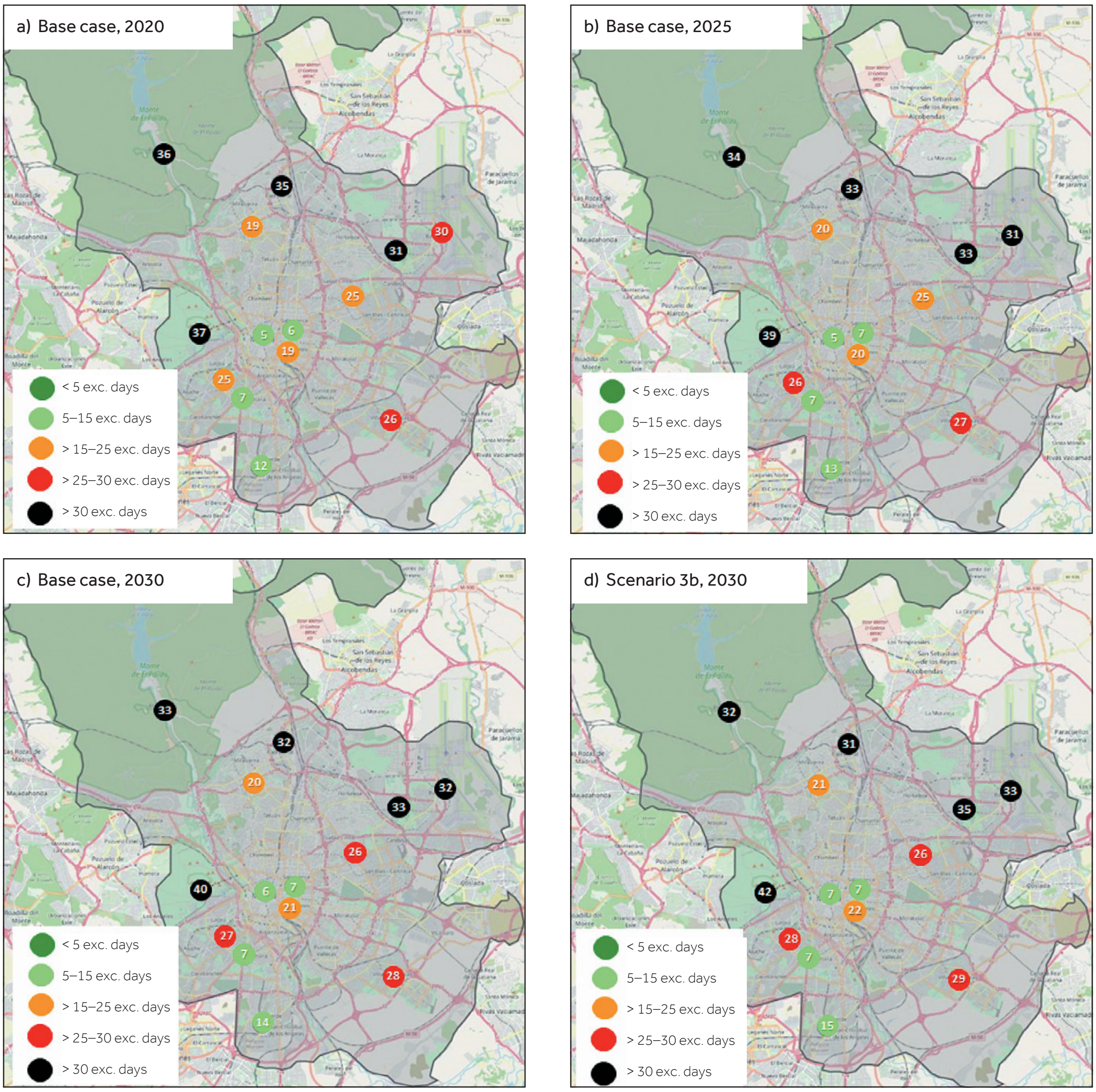
As O_3 is considered a significant pollutant of concern in urban areas, the study analysed the predicted compliance change for O_3 under the current AQLV of 120 µg/m^3 (with an exceedance allowance of 25 days) from 2020 onwards. For this purpose, O_3 compliance under the base case was studied, as well as compliance under some of the emissions scenarios that targeted NO_x and VOC emissions — two important precursors of O_3 formation. Figure 11 shows the modelled compliance of O_3 monitoring stations (urban/suburban) at the European level in 2025 and 2030 under the different scenarios examined in the study.

Figure 11: Predicted percentage of O_3 non-compliant stations in Europe (2025–2030) under the base case and different scenarios examined



By 2025, the already-legislated emission reduction measures as described in the base case will result in about 88% of European monitoring stations (urban/suburban) achieving the current EU AQLV of 120 µg/m^3 (not to be exceeded on more than 25 days) with an additional slight improvement in 2030. However, even in 2030, the remaining 10% of monitoring stations are predicted to record exceedances in O_3 concentrations for more than 25 days. A very limited further improvement in the base case situation is also predicted in all 'beyond the base case' road transport scenarios examined. This limited further reduction in O_3 concentrations in urban areas can, to a large extent, be explained by the NO titration effect.[16,17,18] NO_2 is a precursor of O_3, but O_3 is consumed by reaction with NO. In the presence of high NO concentrations, O_3 concentration values can become very low. The removal of O_3 by reaction with NO to form NO_2 is called titration. When NO_x concentrations are in excess, as is usually the case in urban areas, the further reduction of NO_x could potentially favour the formation of O_3 due to the loss of the titrating effect of NO on ozone, and could eventually offset any reduction in O_3 that results from the emission reduction measures described in the base case. This is particularly evident when looking at the results at the individual city centre level, where O_3 exceedance days are predicted to increase in the base case with time, with further increases in O_3 concentrations when introducing additional measures targeting road transport (see Figure 12 on page 46, which shows the results for Madrid as an example).

Figure 12: O_3 monitoring station compliance in Madrid under the base case in 2020, 2025 and 2030, and under the diesel passenger car scenario 3b in 2030



Targeting VOC emissions from road transport, as well as from the distribution and storage of gasoline, appears to be ineffective in improving O_3 compliance in the future, as all scenarios examined in the study suggest a change of ±1.5% in the number of O_3 non-compliant stations compared to the base case. Findings from recent studies suggest that a more effective strategy to reduce O_3 concentrations and improve compliance, especially in urban areas, is to target NMVOC emissions from the solvent and product use sector.[10]

Conclusions

Concawe recently undertook two modelling studies focusing on the contribution of road transport emissions to overall air quality in urban areas of Europe with a particular focus on concerns over non-compliance with the annual AQLVs for NO_2 and PM. Among other important findings, the study concluded that the fleet turnover from older vehicles to new vehicles (i.e. specifically to Euro 6d compliant vehicles) will improve air quality compliance in a comparable way with the results of a widespread deployment of zero-emission vehicles.

In the context of compliance improvement, this study followed the same methodology used in the earlier UAQ studies and extended the focus to explore whether further actions on emissions sectors could potentially improve compliance in Europe, and in major urban cities in particular. Road transport was the core focus of the assessment through a number of scenarios exploring the effects of various rates of substitution of diesel-powered road transport vehicles (e.g. passenger cars, light-duty commercial and heavy-duty vehicles) with electric-powered vehicles undertaking the same level of activity. Additional emission reduction scenarios from other urban sectors were also explored to improve understanding of the contribution of road transport to improving compliance compared to other sources.

Results from the modelled scenarios have shown the following:

- Already-legislated measures, as described in the updated base case scenario, will result in a high degree of NO_2 compliance with the current EU AQLV across Europe from 2020 onwards (with almost 99% of EU monitoring stations being compliant by 2030). This is in accordance with the findings of previous UAQ studies.
- All additional 'beyond the base case' road transport scenarios, assuming increased (up to 100%) rates of substitution of the pre-2020 diesel-powered vehicle fleet with electric-powered vehicles, will improve NO_2 compliance in the shorter term (between 2020–2025), but post 2025 their impact will be limited. In addition, any scenario targeting NO_x emissions from the domestic sector will also offer a negligible improvement in NO_2 compliance.
- Any remaining exceedances of NO_2 are likely to be addressed through targeted and city-specific measures rather than through further EU-wide and/or national emissions reductions. This would require a thorough and robust source attribution analysis to better understand the contribution of the vehicle segment and other sources.
- Non-compliance will, however, become an EU-wide issue if the current EU NO_2 AQLV is lowered to align with the recently revised WHO air quality guideline value. In all scenarios examined in the study, 30% (or more, depending on the scenario) of EU monitoring stations will record exceedances.
- $PM_{2.5}$ is predicted to achieve nearly complete compliance across the EU in 2025, under the base case scenario. Any additional measures to mitigate exhaust PM emissions from road transport will only offer a limited further improvement in $PM_{2.5}$ compliance, and only in the shorter term, while post 2025 the impact will be negligible.

- Further emission controls or fuel substitution of solid fuel burning in the domestic sector is predicted to be the most effective strategy for reducing $PM_{2.5}$ concentrations and addressing any remaining exceedances. This will be an important point in any (likely) future alignment of the current EU $PM_{2.5}$ AQLV with the (lower) WHO air quality guideline value, which would impose significant and widespread $PM_{2.5}$ non-compliance issues in the EU.
- O_3 will be reduced from 2025 onwards with the measures implemented under the base case, and compliance will be achieved at around 90% of EU monitoring stations.
- None of the 'beyond the base case' road transport scenarios examined will offer a significant further improvement in O_3 compliance. Indeed, further reductions in NO_x emissions and the accompanying loss of NO titration could eventually lead to an increase in the number of O_3 exceedance days, making O_3 compliance even more challenging.

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Fifty years of European oil pipeline safety and environmental performance statistics

For the past 50 years, Concawe has been committed to the collection and reporting of data on the performance of the European cross-country pipeline network. The results have been published annually in Concawe's oil pipeline performance report which has become a valuable tool for supporting pipeline operators, pipeline designers, regulators and industry actors in the continued management of the safety and integrity of European oil pipelines.

Authors

Members of OPMG/STF-1 annual *Performance of European cross-country oil pipelines* report

At the beginning of the 1970s, Concawe, then a young organisation less than 10 years old, launched a new activity aimed at recording loss-of-containment incidents affecting European cross-country oil pipelines, including their consequences (environmental impact, fires, injuries and/or fatalities) and the underlying causes. Data were collected by way of an annual survey covering Concawe member companies and their affiliates, as well as other European pipeline operators that agreed to participate. The information collected was transferred into a database from which a range of statistics were derived as a means of monitoring the performance of European oil pipelines over time. This activity has now been sustained for the past 50 years with publication of the results in an annual report, from the first one published in 1972 covering incidents recorded in 1971, to the latest edition covering incidents recorded up to 2020. Over the years, the *Performance of European cross-country oil pipelines* report has become one of the most noted Concawe publications, used by pipeline operators, pipeline designers, regulators and industry actors in general to shed light on the risks and potential consequences associated with oil pipeline operations, and to support the learning of lessons from past incidents.

The Concawe pipeline inventory

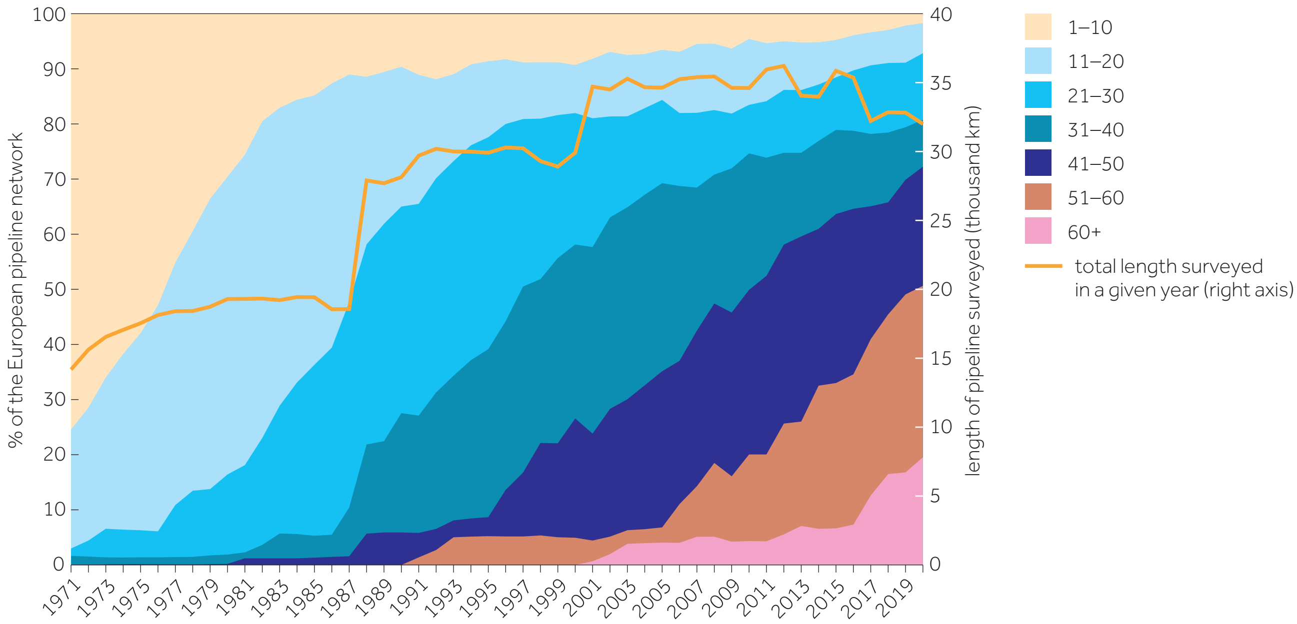
The target inventory includes pipelines used for transporting crude oil or petroleum products, with a length of 2 km or more in the public domain, running cross-country and including short estuary or river crossings but excluding undersea pipeline systems (e.g. for offshore crude oil production). Pump stations, intermediate above-ground installations and intermediate storage facilities are included, but origin and destination terminal facilities and tank farms are excluded. The minimum reportable spillage size has been set at 1 m^3 (1,000 litres) or less where exceptional safety or environmental consequences are reported.

The geographical region covered was originally consistent with Concawe's terms of reference at the time, i.e. OECD Western Europe, which then included 19 member countries, although Turkey was never covered. From 1971 to 1987, only pipelines owned by oil industry companies were included, but from 1988 non-commercially-owned pipeline systems (essentially some of the military/NATO systems) were brought into the inventory. Following the reunification of Germany, the pipelines in former East Germany (DDR) were added to the database from 1991. This was followed by Czech and Hungarian crude and product lines in 2001, Slovakian crude and product lines in 2003 and some of the Croatian crude lines in 2007. From 2013 additional Croatian crude lines were included. The larger pipeline systems that are not included in the current inventory are NATO pipelines in Denmark, Italy, Greece, Norway and Portugal, as well as all crude and product pipelines in Poland.

In 2020, the survey was targeted at 72 operators, and information was received from 68 of these. They cover a total length of nearly 35,000 km, slightly less than a third of which transport refined products, with the balance transporting crude oil. Historically, a small proportion of insulated pipelines transported hot products (mostly heavy fuel oil) but these have gradually been taken out of service as (external) corrosion under insulation was responsible for a number of pipeline failures. Today only about 50 km remain in service.

When the Concawe survey was first performed in 1971, some 70% of the pipelines in the inventory were 10 years old or less. Although the age distribution was quite wide, the oldest pipelines were in the 26–30 years age bracket and represented only a tiny fraction of the total. Over the years, new pipelines were commissioned, some were taken out of service, and existing pipelines were added to the inventory. Although some short sections may have been renewed, there has been no large-scale replacement of existing pipelines. The evolution of the overall age profile (Figure 1) shows that the network has been ageing progressively. By 2020, only 1.5% of the total was 10 years old or less while 72.3% was more than 40 years old. This has presented specific challenges for operators, which are discussed later in this article.

Figure 1: European oil pipeline historical age distribution (1971–2020)



General evolution of performance over time

The annual Concawe survey tracks a number of parameters related to events that have led to loss of containment, including fires, injuries and fatalities. Over the 50-year period, 14 fatalities have been recorded in 5 separate incidents, the latest in 1999. A total of 13 fatalities resulted from a fire in 4 of these incidents, and 1 fatality in 1999 resulted from drowning in a pit filled with product during a theft attempt. Another five incidents involved a fire but without fatalities or injuries. Only three non-fatal injuries (of which two separate events resulted from inhalation/ingestion of oil spray/aerosol) have been recorded, the latest in 2006 (third party injured).

Three single events resulted in multiple fatalities (four in 1975, five in 1979 and three in 1989) caused by delayed ignition of hydrocarbon vapours. This highlights the criticality of securing a spillage area promptly as part of the emergency response and repair procedures (including avoidance of potential ignition sources where volatile products are involved). Similar incidents have been recorded in other world regions, some with much more dramatic consequences.

The bulk of the information collected annually concerns oil spillages and includes the following:

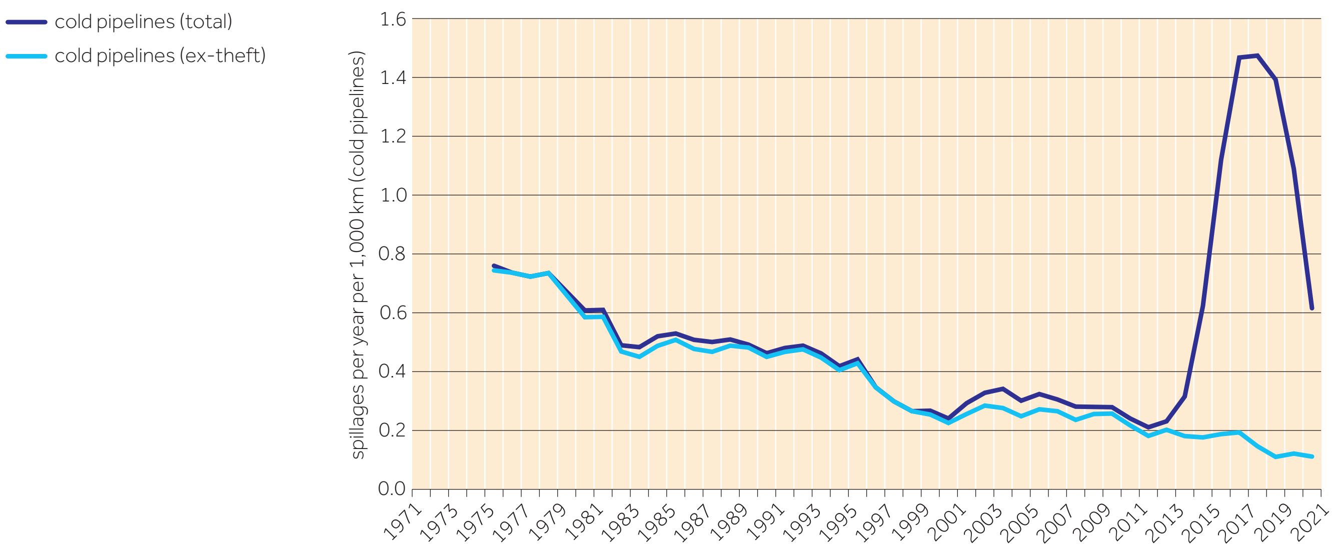
- Data related to the impact and consequences, such as the type of facility (under/overground pipe, pump station), type of area (e.g. residential, industrial, agricultural), volume spilled and recovered, ground area and contamination of water bodies.
- Information on how the leakage was discovered and dealt with.
- The cause of the spillage: causes are split into five main cause categories, namely 'Mechanical', 'Operational', 'Corrosion', 'Natural hazards' and 'Third party'. Each main cause is then divided into a number of subcategories.

Because of the changes in the inventory covered by Concawe over the years, statistical data expressed in terms of frequency (per 1,000 km of pipeline) are more informative than absolute numbers.

Number and frequency of spillages

Over the whole 50-year period 780 spillages have been reported. Two hundred and seventy-two of these were related to theft attempts, a phenomenon that, although recognised previously, has become a major issue in the past 10 years (see discussion later in the article). Another 68 events occurred in the 'hot' pipelines (54 of which were due to external corrosion). Figure 2 shows the five-year moving average of the spillage frequency for cold pipelines (i.e. not 'hot' pipelines), both including and excluding theft events.

Figure 2: 45-year trend in spillage frequency (cold pipelines, moving average)



For cold pipelines, excluding theft, spillages have followed a long-term downward trend from more than 0.7 spillages per 1,000 km in the early 1970s to 0.12 in 2020. To avoid the obvious distortion of the long-term statistics created by the recent spike in theft-related incidents, figures are presented with and without theft-related events where appropriate. Table 1 summarises the key data for cold pipelines per decade and over the full period.

Table 1: Cold pipelines exposure, number of incidents and incident frequencies (including and excluding theft)

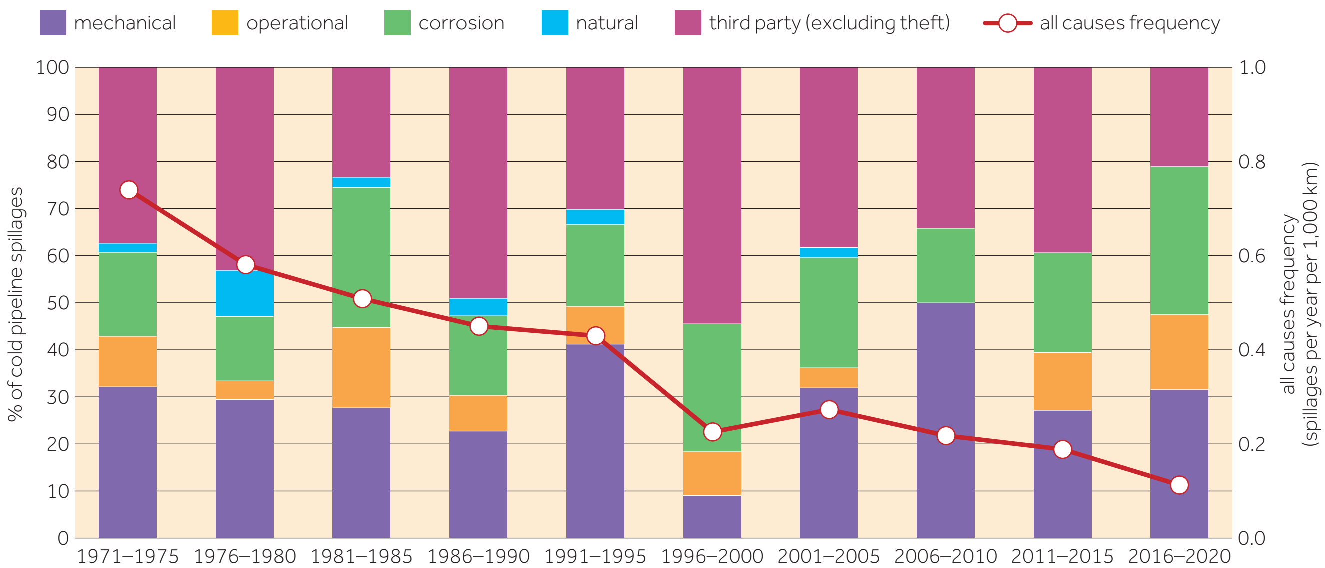
Period	Exposure (1,000 km/year)	Incidents (excluding theft)	Thefts (with spill)	Fatalities	Injuries	Failure frequency per 1,000 km/year (excluding theft)	Failure frequency per 1,000 km/year (including theft)
1971–1980	163	107	3	9		0.66	0.67
1981–1990	210	100	3	3	2	0.48	0.49
1991–2000	293	96	4	2		0.33	0.34
2001–2010	347	85	13		1	0.24	0.28
2011–2020	345	52	249			0.15	0.87
Full period 1971–2020	**1,359**	**440**	**272**	**14**	**3**	**0.32**	**0.52**

The failure frequency for hot pipelines is an order of magnitude higher as a consequence of widespread external corrosion issues. As mentioned above, the issue was recognised by the industry, and the bulk of these lines have now been closed down (or converted to cold service) and the problem has been substantially alleviated.

Causes of spillages

Figure 3 shows the evolution, in five-year periods from 1971 to 2020, of the non-theft-related spillage frequency for cold pipelines, broken down according to the five main causes listed on page 52 (440 spillages in total). The overall decreasing trend shown in Figure 3 is again apparent, albeit a more complex picture when looking at the individual cause categories.

Figure 3: Cold pipelines spillage frequencies by cause (1971–2020)



Third-party activities (excluding theft)

Third-party activities (excluding theft) have caused the largest number of spillages. There have been fewer cases in recent years, and hence the cause structure has become more balanced.

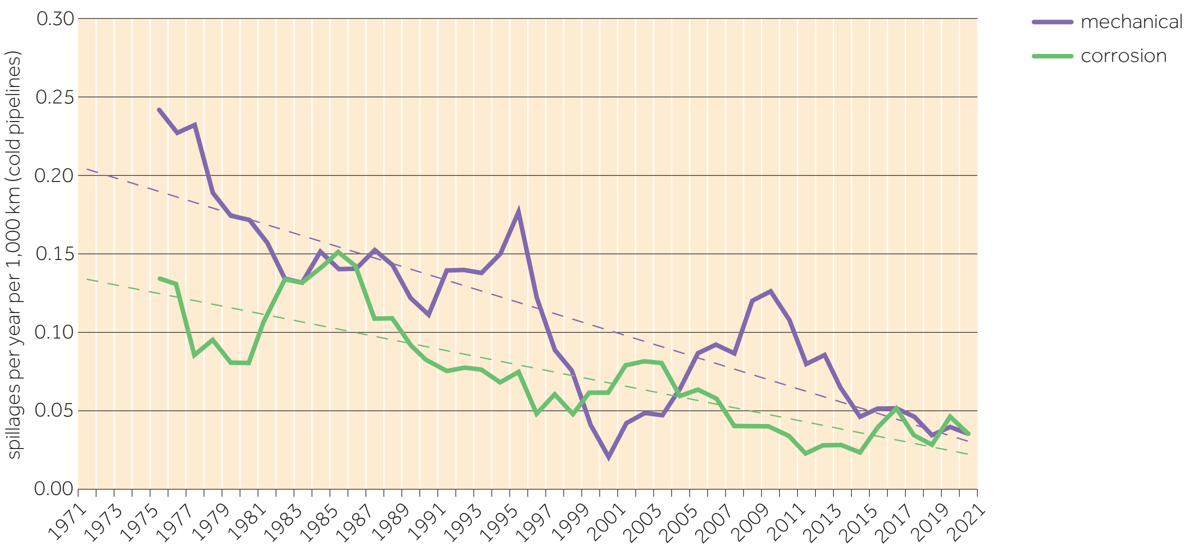
Pipelines run over long distances, predominantly below ground, and through diverse areas. As such, they are vulnerable to accidental damage caused by parties involved in digging and other earth-moving activities. This has been an issue since buried pipelines were first laid. A variety of measures have been put in place over the years, including: marking; physical protection; enhanced surveillance; regular contacts with landowners, utility organisations and civil contractors; and, in some countries, the development of so-called 'one-call systems'. The latter are specifically designed to encourage (or, in some countries, obligate) potential 'excavators' to declare their intentions in advance. These measures, although partly successful, require continual review and adaptation and, although the frequency of related incidents has followed a downward trend, accidental third-party interference remains one of the major causes of spillage for oil pipelines.

Mechanical and corrosion

The 'Mechanical' category encompasses failures due to design, material or construction defects (e.g. incorrect material, faulty weld, fatigue). The 'Corrosion' category encompasses failures that have developed from internal or external corrosion. In a small number of cases, cracking due to corrosion under stress has been included as the failure cause.

Data on the frequency of spillages in both categories show a long-term downward trend since the early 1980s, albeit with notable shorter-term peaks and troughs (Figure 4).

Figure 4: Frequency of mechanical and corrosion-related spillages for cold pipelines (five-year moving average)



Over the past two decades, operators and regulators became concerned that ageing pipelines may be increasingly prone to mechanical (e.g. fatigue) or corrosion-related failures. The spike in mechanical failures observed over the decade after the millennium caused particular concern in this respect, but the downward trend has resumed in the past ten years. A relatively high number of corrosion cases was reported in the past decade suggesting that the trend may be flatlining.

A detailed analysis of the data did not reveal any significant correlation between the incident frequency of either mechanical (fatigue-related or otherwise) or corrosion failures and the actual age of the pipeline at the time of failure.

The sophisticated integrity management and maintenance systems developed over the years, including the use of new techniques such as internal inspection with intelligent tools, have doubtless played a key role in maintaining the safe and reliable operation of pipelines and will continue to be an essential tool in the future. Concawe pipeline statistics, in particular those covering the mechanical and corrosion incidents, will continue to be used to monitor performance.

Volume spilled

The volume spilled varies a great deal from event to event, and statistics can be heavily skewed by a few very large spills that occur from time to time. Furthermore, it is not always possible to determine the spillage figures accurately, for instance when small leaks have continued for a period of time before being detected. In the majority of theft cases, the product loss is always a combination of an unknown volume of stolen fuel and product spillage.

The annual spilled volume has decreased steadily over time, mostly as a consequence of the reduced number of spills, with the average volume per spill remaining in the same ball park.

Nearly 50% of above-ground facilities, including pump stations, were detected by pipeline company resources. Underground pipeline leaks were often first detected by a third party (nearly 50%), sometimes by those who caused the incident in the first place. Dedicated automated leak detection systems were involved in detecting only 15% of those spillages over the full survey period, although this has increased gradually since the 1980s to nearly 30% in recent years as a result of the increased use of such systems and their technological improvements. Routine monitoring by pipeline operators (using pressure and flow data) and leak testing (based on pressure and temperature monitoring) when the pipeline is temporarily shut in have also played their part in detecting leaks (nearly 30% of the spillage cases). It should also be noted that the majority of leaks are small and hence reliable detection is a challenge for leak detection systems.

As a rule, a high proportion of the initially spilled product volume is recovered (on average about 60%) either as liquid or in the soil that is excavated as part of the cleaning process.

Product theft: a new threat that is being vigorously and successfully addressed

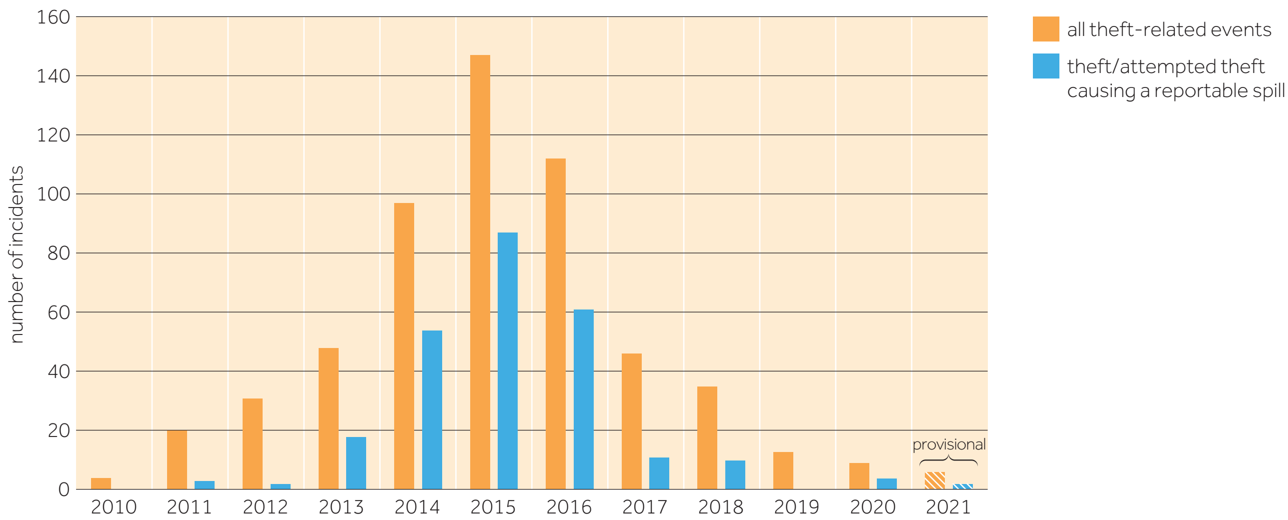
Because of the nature of their location and the fact that they transport valuable commodities, oil pipelines have always been a potential target for criminals, vandals and even terrorists. Up to the beginning of the past decade, only a few incidents involving any of the above were recorded in Europe (less than one incident per year on average), mostly related to theft attempts and geographically concentrated in South-Eastern Europe.

From 2011, there was a sharp increase in the number of theft attempts, culminating at 147 in 2015, 87 of which led to a spill. These occurred in several different countries across the continent, often with evidence of sophisticated criminal operations.

In addition to the potential loss of product and/or disturbance to operations, such interference with pipelines, which can involve drilling through the pipeline to install a small-bore connection, can also lead to serious environmental damage, and potentially injuries or even fatalities.

Faced with this serious new threat, operators reacted promptly, enhancing physical surveillance, improving leak detection system capabilities, increasing awareness of the problem with own staff, contractors and law enforcement authorities, and enhancing capability for a fast response and quick repairs. Relevant information was shared within Concawe, and good practices established and disseminated to pipeline operators. These efforts have paid off, and the trend was reversed with 112 events recorded in 2016, 46 in 2017, 35 in 2018, 13 in 2019 (with no reportable spill) and 9 in 2020 (Figure 5). Indications are that the downward trend continued in 2021 with a provisional total of six incidents and two spills. Nonetheless, the annual rate is still above the 50-year average, requiring continued focus and vigilance.

Figure 5: Theft-related events and the associated number of spills (2010–2021)



Improving pipeline integrity and mitigating failure consequences through technology

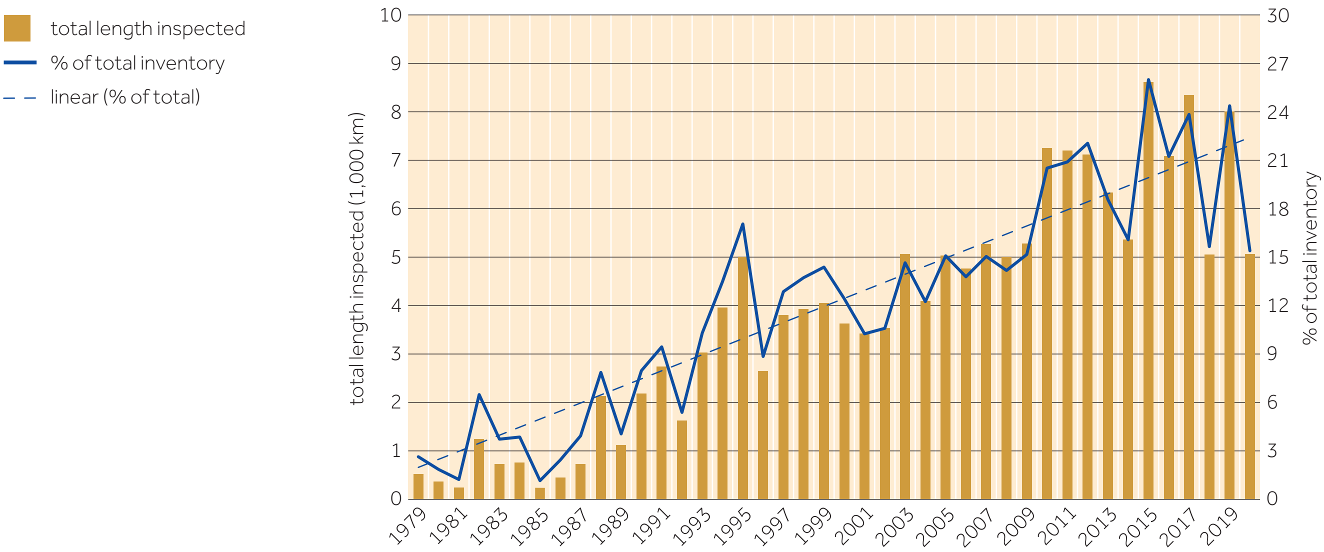
The Concawe annual performance report has supported operators in the implementation of pipeline integrity management systems, to both improve pipeline integrity and mitigate the consequences of integrity failures through technology. Typical elements of these systems include the following:

- Intelligent tools to inspect the pipelines for internal corrosion, external corrosion, cracks and dents, to provide assurance of the integrity of the pipelines and to allow planning of suitable repair strategies, for example to prevent an area of corrosion progressing to a leak and a potential spillage. These tools are referred to as metal loss tools, crack detection tools and geometry tools.
- Various techniques to monitor the pipeline coating and the effectiveness of the cathodic protection systems, e.g. CIPS (close interval potential surveys) and DCVG (direct current voltage gradient). These monitoring processes provide assurance that the protection systems are working effectively, together with information on potential remedial works that may be required to prevent failures.

- Intelligent tools to provide detailed GPS (global positioning system) data for the pipelines that can be overlaid onto geographic information mapping systems (GIS) to support the management of third-party activities close to the pipelines.
- Increased use of more sophisticated dedicated pipeline leak detection systems (metering, pressure wave, etc.) to monitor for pipeline leaks, and also identify and locate pipeline theft events.
- Tools for the detection of pipeline leaks and theft events (inspection 'pigs').
- Photographic and video systems to support the regular aerial inspection of pipelines.
- Innovative repair techniques such as composite materials for pipeline repair in the event of corrosion or damage, and techniques that enable pipeline fittings to be quickly secured following a theft (including temporary encapsulation of the fitting) to ensure the integrity of the pipeline and allow safe operation to be resumed.

Concawe's *Performance of European cross-country oil pipelines* report provides a summary of how the use of intelligent tools for internal inspection has increased over the years (Figure 6). The use of such tools grew steadily up to the mid-1990s, stabilising at around 12% of the inventory every year, and then increased further to around 15% of the inventory in the first decade of the new millennium, and reached more than 20% in the past decade.

Figure 6: Annual length inspected by intelligent tools



The way forward

For the past 50 years, the Concawe's *Performance of European cross-country oil pipelines* report has been a valuable tool for supporting pipeline operators, pipeline designers, regulators and industry actors in the continued management of the safety and integrity of European oil pipelines. Faced with the challenge of an ageing infrastructure and, in recent years, the new threat caused by theft activities, pipeline operators have responded with enhanced integrity management systems, assisted by technological developments in the fields of inline inspections and leak detection systems. As a result, the industry has seen the number and severity of incidents decrease over the past 50 years. Concawe remains committed to providing the framework for the confidential collection and reporting of data, as well as a forum for European pipeline operators to share non-commercially sensitive information, leading to continuous improvements in safety and integrity management.

Abbreviations and terms

AQLV	Air Quality Limit Value
ASC	Ammonia Slip Catalyst
AT	After-Treatment
B5	Diesel fuel blend containing up to 5% biodiesel
B30	Diesel fuel blend containing 30% biodiesel
Bio-LNG	Liquefied Natural Gas made from organic wastes
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
cDPF	Coated Diesel Particulate Filter
CH_4	Methane
CIPS	Close Interval Potential Survey
CNI	Cetane Number Improver
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CRP	Contra-Rotating Propeller
CV	Commercial Vehicle
DCVG	Direct Current Voltage Gradient
DDR	Deutsche Demokratische Republik (German Democratic Republic— former East Germany)
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
2-EHN	2-Ethyl-Hexyl-Nitrate
EC	European Commission
ECU	Electronic Control Unit
EEA	European Environment Agency
EN 590	European Standard that defines the properties that diesel fuel must meet to be sold in the European Union
EU	European Union
EU-27	The 27 member countries of the European Union
EUA	European Union Allowances (i.e. carbon credits)
EU ETS	European Union Emissions Trading System
FAME	Fatty Acid Methyl Ester
FCEV	Fuel Cell Electric Vehicle
FT	Fischer Tropsch
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information System
GPS	Global Positioning System
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies
HC	Hydrocarbons
HD	Heavy Duty
HFO	Heavy Fuel Oil
HDV	Heavy-Duty Vehicle
HP-EGR	High-Pressure Exhaust Gas Recirculation
HVO	Hydrotreated Vegetable Oil
ICCT	International Council on Clean Transportation
ICEV	Internal Combustion Engine Vehicle
IIASA	International Institute for Applied Systems Analysis
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ITF	International Transport Forum
kW	KiloWatt
LAP	Large Area Propeller
LDV	Light-Duty Vehicle
LLV	Legislated Limit Value
LNT	Lean NO_x Trap
MDO	Marine Diesel Oil
MJ	MegaJoule
N_2O	Nitrous Oxide
NATO	North Atlantic Treaty Organization
NEDC	New European Driving Cycle
NH_3	Ammonia
Nm	Newton-Metre
NMVOC	Non-Methane Volatile Organic Compound
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
NPV	Net Present Value

Abbreviations and terms

(continued)

O_3	Ozone
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OGCI	Oil and Gas Climate Initiative
PC	Passenger Car
PCD	Diesel Passenger Car
PDF	Paraffinic Diesel Fuel
PID	Propulsion Improving Device
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter with an aerodynamic diameter less than 2.5 µm
PN	Particulate Number
pSCR	Passive Selective Catalytic Reduction
PNA	Passive NO_x Adsorber
RCP	Representative Concentration Pathway
RDE	Real Driving Emissions (test)
Ro-Ro	Roll-On/Roll-Off
SCR	Selective Catalytic Reduction
SCRF	SCR — Filtered
T95	Temperature at which 95% v/v of a fuel is evaporated
TfL UIP	Transport for London Urban Inter-Peak (test cycle)
TSAP	Thematic Strategy on Air Pollution
TTW	Tank To Wheels
UAQ	Urban Air Quality
UCOME	Used Cooking Oil Methyl Ester
UK	United Kingdom
US	United States
USD	US Dollars
VOC	Volatile Organic Compound
WHO	World Health Organization
WHR	Waste Heat Recovery
WHVC	World Harmonized Vehicle Cycle
WLTC	Worldwide harmonized Light-duty Test Cycle
WPE	(TSAP) Working Party for the Environment
WTT	Well To Tank
WTW	Well To Wheels
XTL	X-to-Liquid — a process for converting a solid or gaseous energy carrier, i.e. gas, biomass or coal, to a synthetic liquid fuel (e.g. gas-to-liquid; biomass-to-liquid, etc.)

Concawe reports and other publications

Concawe reports

7/22	Petroleum refinery effluent contribution to chemical mixture toxic pressure in the environment
6/22	Performance of European cross-country oil pipelines — Statistical summary of reported spillages in 2020 and since 1971
5/22	User Manual for Concawe LNAPL Toolbox
4/22	Definition Guidelines of Water Reuse, Recycling and Reclamation for European Refinery Sector
3/22	Impacts of low carbon technologies on environmental parameters: air/water/waste
2/22	Literature review of Particulate Matter (PM) from transport with a special focus on organic aerosols
1/22	Hazard classification and labelling of petroleum substances in the European Economic Area - 2021

Scientific papers

Carrillo, J-C *et al.* (2022). 'Comparison of PAC and MOAH for understanding the carcinogenic and developmental toxicity potential of mineral oils. In *Regulatory Toxicology and Pharmacology*, Vol. 132.

Fraunhofer IBP (2022). *Biodiversity Impact Assessment of future biomass provision for biofuel production – Phase 1*.

Fraunhofer IBP (2022). *Biodiversity Impact Assessment of future biomass provision for biofuel production – Phase 1* (Excel™ file accompanying the report).

Concawe (2022). *Fleet & Fuels pathways for a carbon-neutral road transport in Europe by 2050: a review of possible options.*

Ricardo (2022). *Technological, Operational and Energy Pathways for Maritime Transport to Reduce Emissions Towards 2050.* Final report.

Sjøholm, K. K. *et al.* (2022). 'Linking biodegradation kinetics, microbial composition and test temperature – Testing 40 petroleum hydrocarbons using inocula collected in winter and summer'. In *Environmental Science: Processes and Impacts*, Vol. 24, No. 1.

Concawe reports and other publications *(continued)*

Scientific papers *(continued)*

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Whale, G. F. *et al.* (2022). Assessment of oil refinery wastewater and effluent integrating bioassays, mechanistic modelling and bioavailability evaluation'. In *Chemosphere*, Vol. 287, Part 3.

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