Fuel effects on modern diesel passenger car and commercial vehicle emissions

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

Rod Williams (Shell, Concawe)

Roland Dauphin (Concawe)

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.

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

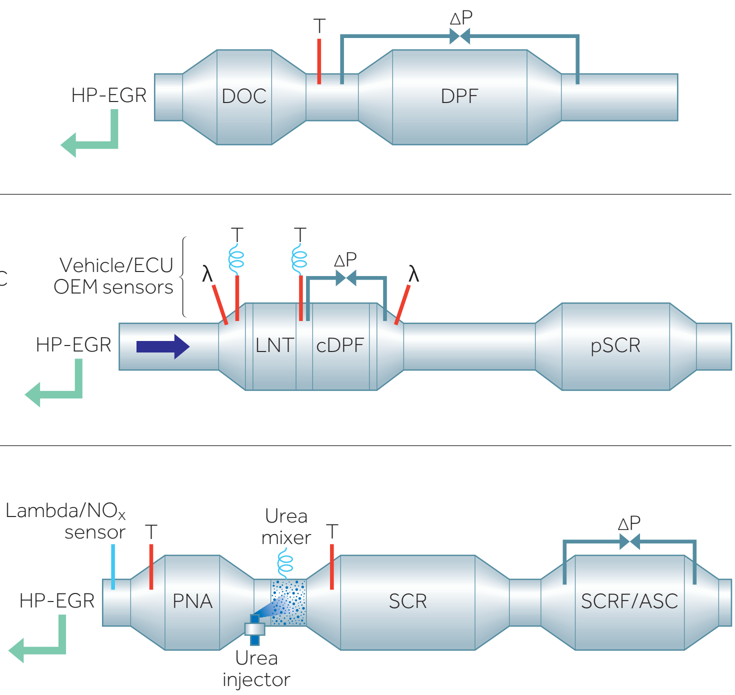
	Car A	Car B	Car C
Emissions certification	Euro 5b	Euro 6b	Euro 6d-TEMP
Year of registration	2013	2016	2017
Engine capacity (litres)	1.6	1.5	1.5
Vehicle mileage at start of test (km)	91,000	10,000	6,000

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

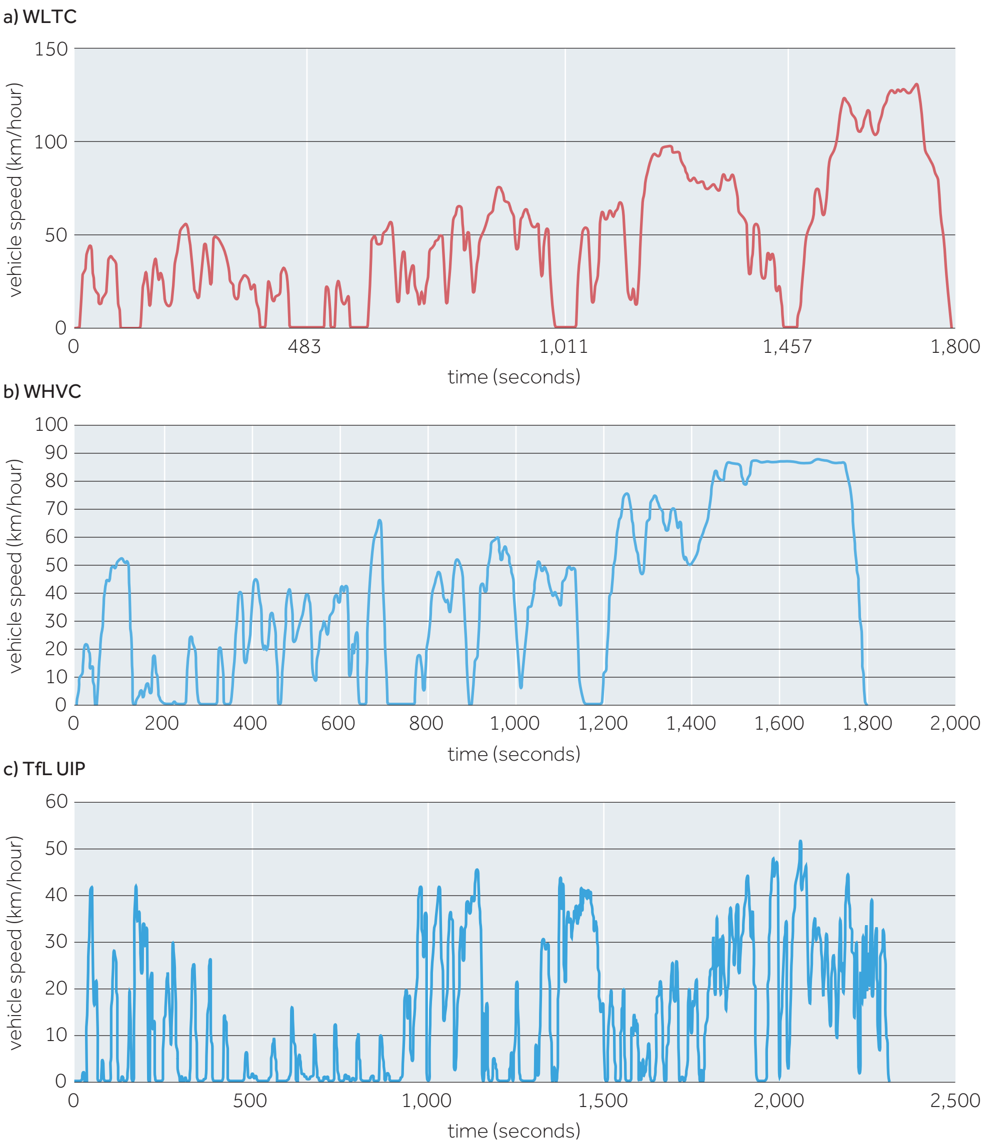
ASC: ammonia slip catalyst

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

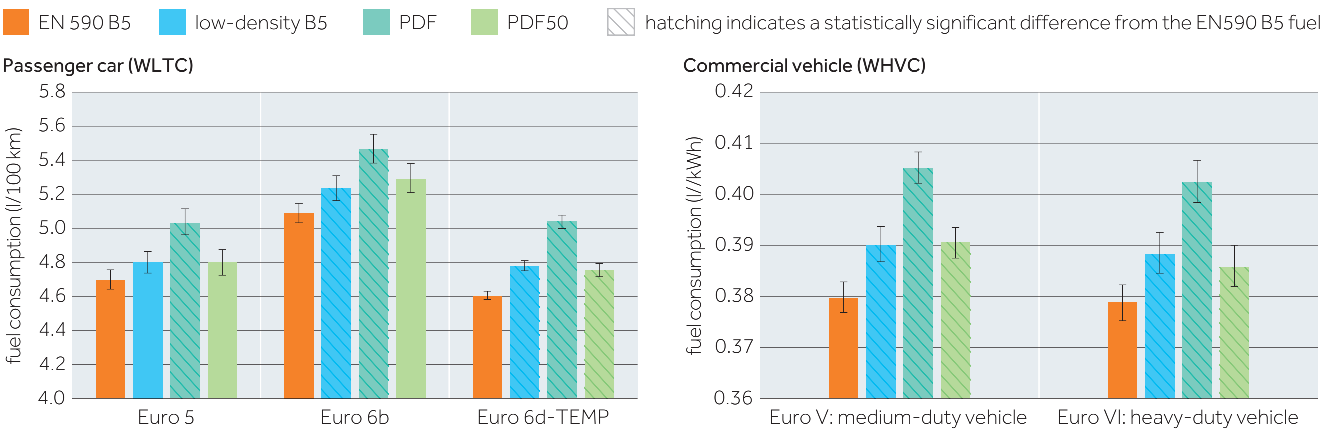
Fuel consumption, CO_2 emissions and total greenhouse gases

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

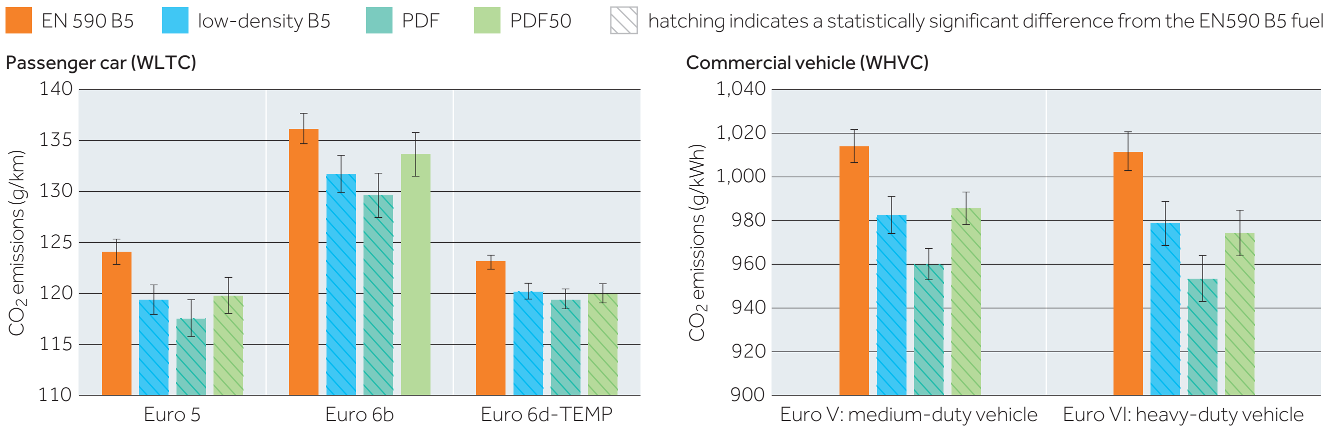
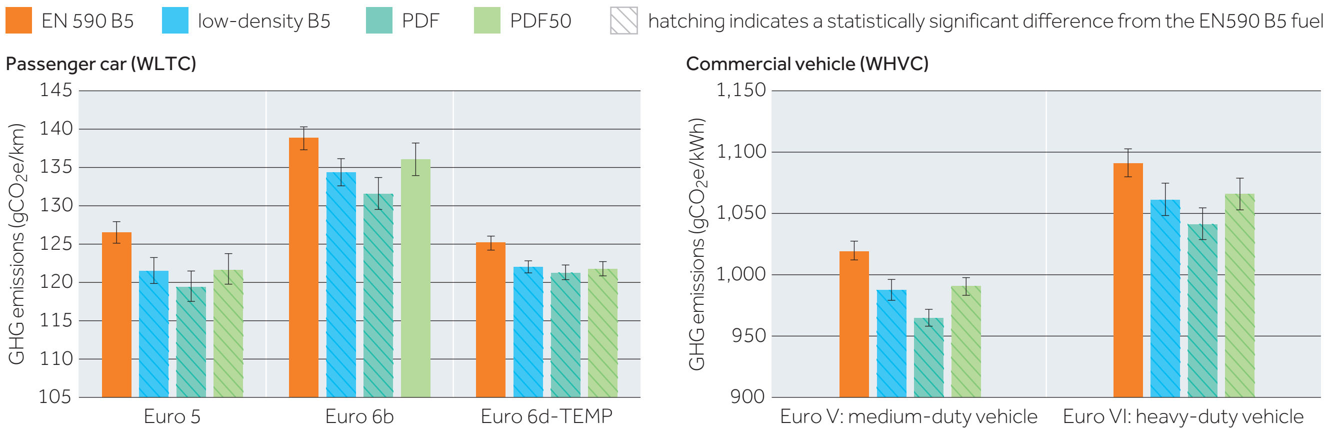


Figure 6: Low-density fuel effects on GHG emissions



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)

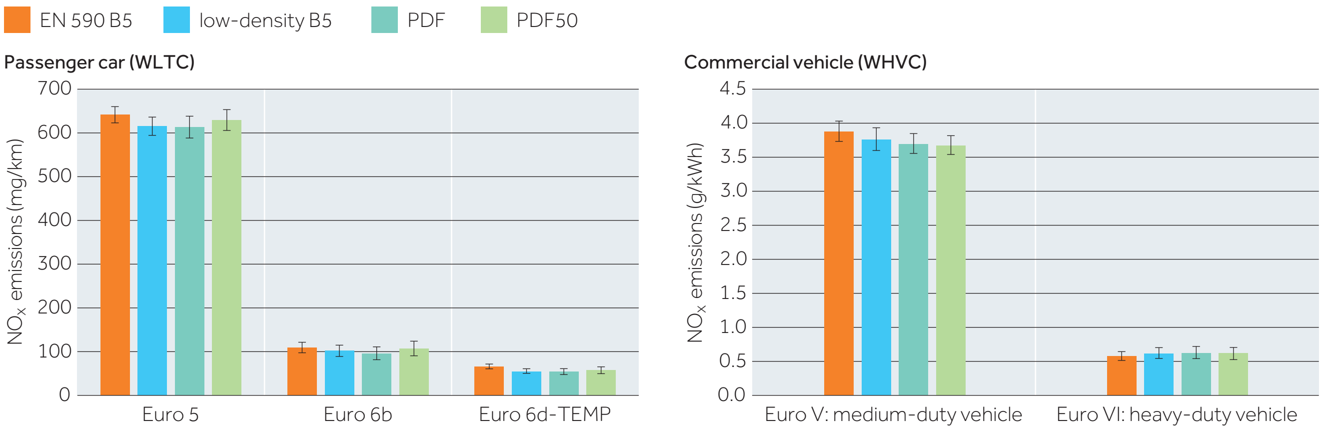


Figure 8: Low-density fuel effects on NO_x emissions — engine-out versus tailpipe

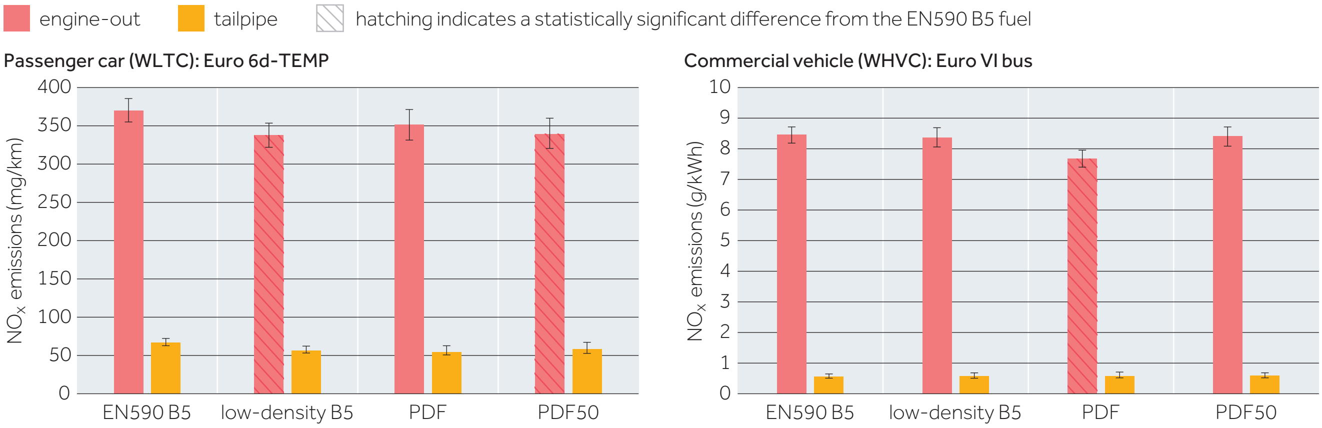
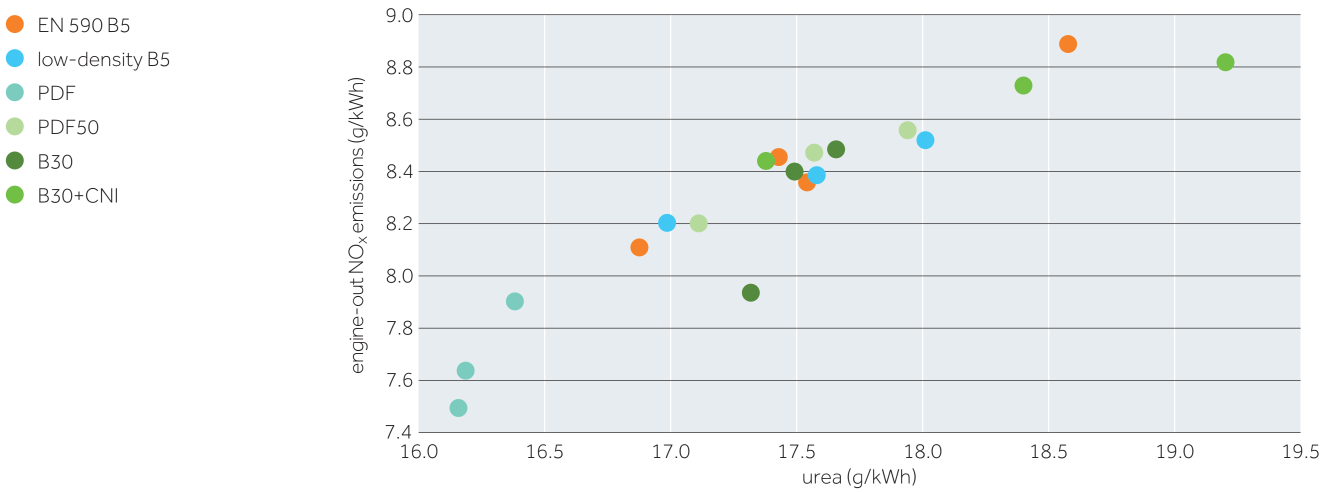


Figure 9: Correlation between engine-out NO_x and AdBlue (urea) consumption — Euro VI bus, WHVC
(results show a reduced AdBlue consumption for PDF)



Summary of other results with the low-density fuels set

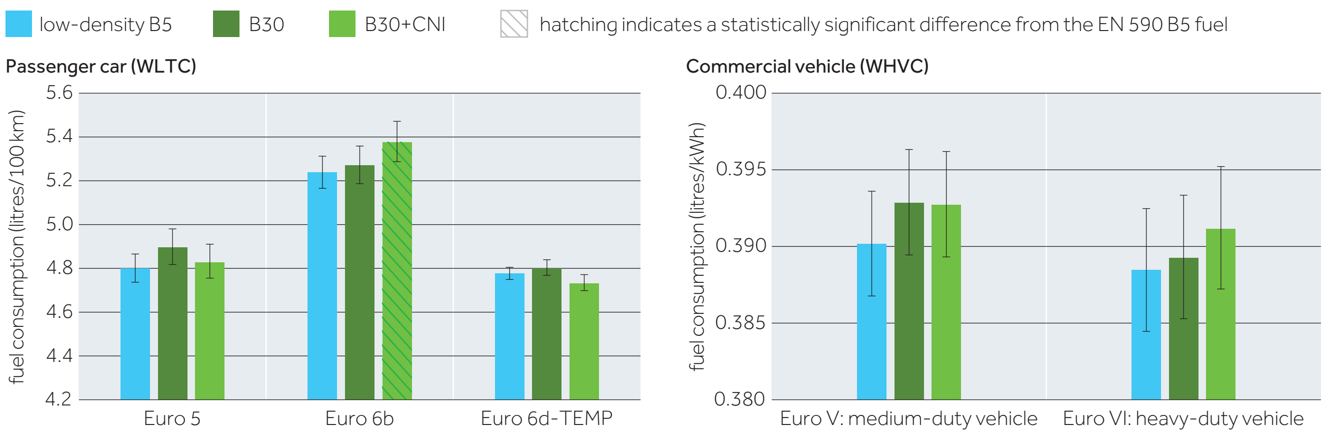
- No statistically significant effects on tailpipe PM and PN emissions were observed, except for reduced PM emissions with some low-density fuels from the Euro V truck which had no DPF.
- Significant effects were observed on CO and HC in some cases, tending to be reduced with low-density fuels.
- Ammonia (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

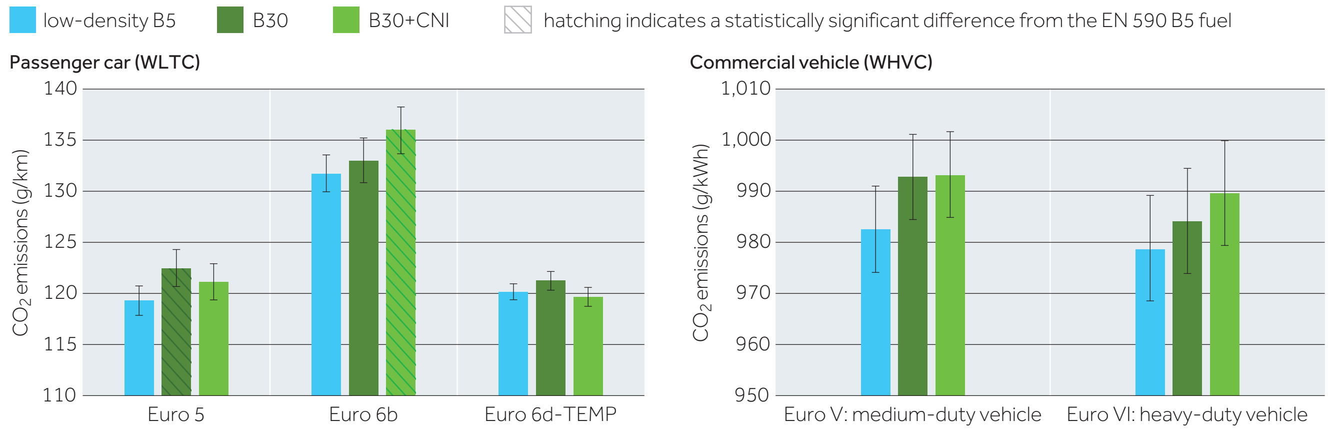
Volumetric fuel consumption was generally unchanged with B30 compared to the low-density B5 fuel, due to there being no impact of FAME on volumetric energy content or efficiency (Figure 10). While it may seem surprising that the volumetric fuel consumption is not increased with B30, this is due to the 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.

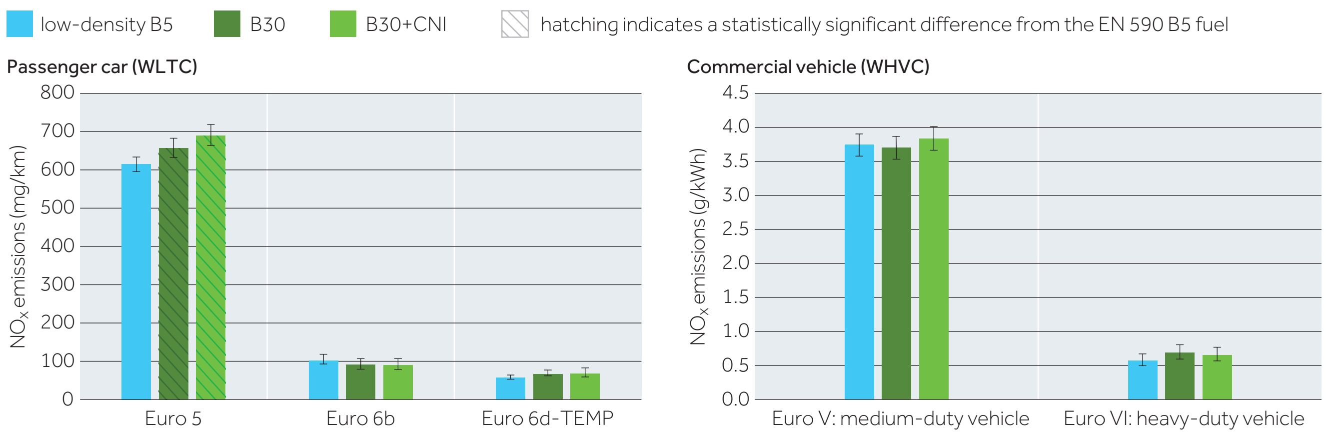
Figure 11: Effects of increasing FAME content (B5–B30) on CO_2 emissions



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).

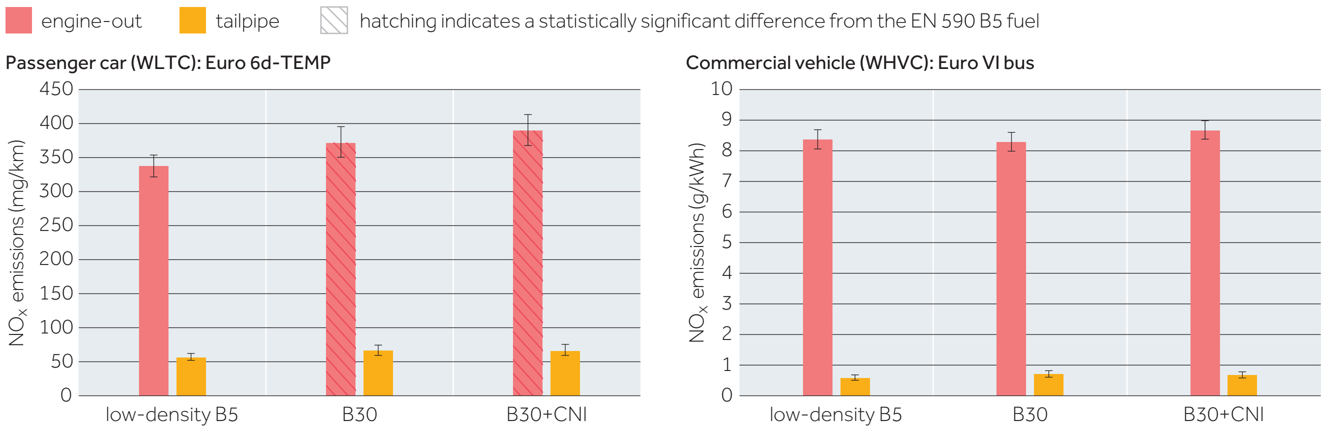
Figure 12: Effects of increasing FAME content (B5–B30) on NO_x emissions
(results show that NO_x emissions only increase with FAME content in the Euro 5 PC, and that the addition of CNI does not mitigate this effect)



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/
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Concawe: https://www.concawe.eu/publication/fuel-effects-on-regulated-and-unregulated-emissions-from-two-commercial-euro-v-and-euro-vi-road-transport-vehicles
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