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ENVIRONMENTAL SCIENCE FOR THE EUROPEAN REFINING INDUSTRY

review

Volume 26, Number 1 • September 2017

Environmental science for the European refining industry

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Foreword

Robin Nelson
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Concawe is working together with our member companies to further improve the energy efficiency in European refineries which will contribute to lower carbon emissions during the manufacture of fuels and other refinery products. In parallel we are working with the transport sector to explore alternative liquid fuels that contribute to better fuel efficiency of vehicles. Finally, Concawe is exploring different opportunities to capture the carbon dioxide (CO_2) emissions. As nearly 80% of the total CO_2 emissions occur when the fuel is consumed, options to either capture the CO_2 at source or to offset the emissions via natural carbon capture projects are worth investigation.

We are grateful to Professor Lars Hein from Wageningen University for the first article in this *Review* which provides an illuminating insight into the mechanisms by which forest carbon credits may be used.

The second article in this *Review* is from the Laboratory of Applied Thermodynamics in Greece, which explores the use of a simulation model for the assessment of CO_2 emissions of passenger cars under real-world conditions.

The third article focuses on emissions from gasoline direct injection engines, demonstrating the value of gasoline particulate filters in meeting the Euro 6d Real Driving Emission limits for particulate number as well as for NO_x. Our thanks to Ricardo who conducted the test work for this project.

The fourth and final article presents a review of European oil pipeline performance for 2015. This article demonstrates that the frequency of spills due to corrosion or other maintenance-related reasons has followed the overall downward trend. However, the review also reveals that spillages resulting from product theft continue to rise. Concawe, together with pipeline operators, has taken action by engaging with law enforcement agencies in Europe to raise awareness of this issue.

Contents

A forthcoming report by Concawe, entitled *Using Forest Carbon Credits to Offset Emissions in the Downstream Business*, examines whether, and how, forest carbon credits can be used to offset emissions from the European refining and road transport sectors. Forest carbon plays an important role in the global carbon cycle, with emissions from land use, land-use change and forestry (LULUCF) amounting to around 10% of total global greenhouse gas emissions. Forest carbon projects aim to reduce emissions from LULUCF and/or use vegetation to capture CO_2 from the atmosphere, particularly in (but not limited to) the tropics. There are two principal types of carbon markets: the compliance market and the voluntary market. Based on an analysis of forest carbon markets and changes therein, several options to use carbon credits in the refining and road transport sector have been explored.

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This article describes a study which investigates the possibility of evaluating real-world CO_2 emissions with generic simulation models, developed on the basis of portable emissions measurements system (PEMS) data on real driving emissions (RDE). The aim is to provide accurate and reliable CO_2 emissions simulations for any modern vehicle model, combined with RDE measurements. It is hoped ultimately to further enhance the development of a methodology for the measurement and evaluation of real-world fuel consumption and CO_2 emissions.

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The market share of gasoline direct injection (GDI) vehicles has been increasing, promoted by its positive contribution to the overall improvement in fleet fuel economy. It has, however, been reported that this type of engine is emitting more ultrafine particles than the Euro 6c particle number (PN) limit of $6x10^{11}$ particles/km that will be introduced in Europe as of September 2017 in parallel with the Real Driving Emission (RDE) procedure.

The emissions performance of a Euro 6b GDI passenger car was measured, first in the OEM build without a gasoline particulate filter (GPF) and then retrofitted with a coated GPF in the underfloor position. Regulated emissions were measured on the European regulatory test cycles (NEDC and WLTC) and in real-world conditions with portable emissions measurement systems (PEMS) according to the published European RDE procedure. Finally, tests were conducted on a chassis dynamometer to explore the impact of going towards the RDE boundary conditions (increasing severity).

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To date, Concawe has collected 45 years of spillage data on European cross-country oil pipelines. At nearly 37,500 km, the current inventory includes the majority of such pipelines in Europe, transporting some 751 million m^3 per year of crude oil and oil products. The latest Concawe pipeline performance report was published in June 2017, and provides spill incident statistics for 2015 and historical trends in causal factors (mechanical failure, operational, corrosion, natural hazard and third party) since 1971. The 2015 data show product theft to be the dominant cause of spillage incidents, with 87 spills associated with product theft and only 6 attributed to other causes. In the absence of product theft, the spill frequency is 0.17 spillages per 1000 km of line, which is similar to the 5-year average and well below the long-term running average of 0.47, which has been steadily decreasing over the years from a value of 1.1 in the mid-70s. This consistent downward trend reflects the ongoing activities of pipeline operators to inspect and maintain the network.

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Using forest carbon credits to offset emissions in the downstream business

Current policy conditions are not generally conducive to the use of voluntary carbon credits in the refining sector. Could the development of 'carbon neutral' petrol and/or diesel fuel using forest carbon credits provide a solution?

This article was written by Lars Hein, Wageningen University.

A forthcoming report by Concawe, entitled *Using Forest Carbon Credits to Offset Emissions in the Downstream Business*, examines whether, and how, forest carbon credits can be used to offset emissions from the European refining and road transport sectors. The work was also presented at the 12th Concawe Symposium held in March 2017.

Forest carbon plays an important role in the global carbon cycle, with emissions from land use, land-use change and forestry (LULUCF) amounting to around 10% of total global greenhouse gas emissions. Vegetation, in particular forests, also act as a carbon sink. Plants sequester carbon from the atmosphere as they grow. Currently, the total global emissions from LULUCF are of a similar magnitude to the sequestration of carbon by ecosystems worldwide. Forest cover and carbon sequestration are generally increasing in the temperate and boreal zones, and deforestation and emissions from LULUCF are concentrated in the tropics.

Forest carbon projects aim to reduce emissions from LULUCF and/or use vegetation to capture CO_2 from the atmosphere, particularly in (but not limited to) the tropics. In this way, carbon credits are generated that, once certified by an independent agency, can be sold on the carbon market. There are two principal types of carbon markets: the compliance market and the voluntary market.

Several compliance markets are operational worldwide, and additional markets are currently being designed. The largest compliance market is the European Union Emission Trading System (EU ETS), which includes emissions from the refining sector, but not from road transport. Forest carbon credits are not allowed to be traded in the EU ETS. However, with a number of restrictions, forest carbon credits are traded in other operational compliance markets including those in California and New Zealand.

The voluntary carbon market has an annual turnover of around 90 million tonnes (Mt) CO_2e. Around one-third of the credits traded on the market are from forest carbon projects. There are two principal types of buyers of these credits: (i) companies offsetting their emissions on a voluntary basis, generally driven by a mix of corporate social responsibility and marketing motivations; and (ii) retailers that sell carbon credits on to consumers, for instance to people that want to offset emissions from air travel that they are undertaking. Both groups purchase roughly half of the credits on this market. Suppliers of carbon credits include specialised companies that develop carbon projects (including forest carbon projects) and, to a lesser degree, NGOs developing carbon credits. Most of the forest carbon credits are generated in developing countries, where land is relatively cheap, forests grow fast due to climatic factors, and where showing additionality of carbon credits is relatively easy given that many tropical countries are subject to deforestation. Currently, there is oversupply on the market. Prices of carbon credits are generally low, ranging from US$ 3 to 10 per tonne CO_2 for forest carbon projects.

Both the compliance and voluntary carbon markets are highly dynamic. In addition, in the context of the Paris Agreement, the EU is designing the Effort Sharing Regulation (ESR), which will involve compulsory emission reduction targets for member states including all sectors that are not covered by the EU ETS. LULUCF credits are likely to become part of the ESR (with restrictions on quantity and type), however it is still unclear whether this would include credits generated outside of the EU.

A key factor that may drive changes in the voluntary market is the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which would involve airline companies purchasing carbon credits to achieve the sector's aspirational goal of no net increase in CO_2 emissions from international aviation as of 2020. This would require a volume of credits, beyond 2020, which is several times the size of the current voluntary market volume. Implementing the CORSIA initiative would depend upon an increase in the supply of carbon credits on the voluntary market. The carbon credit sector has shown to be responsive to increases in demand in the past, and may scale up the development of carbon credits rapidly if demand were to increase. The aviation sector may also tap into unused Clean Development Mechanism (CDM) carbon credits (generated as part of the Kyoto Protocol), which are now offered by the UN Climate Change Secretariat under the label of the Climate Neutral Now (CNN) initiative. Several companies have endorsed the

CNN initiative and purchased CDM credits. However, the additionality of the CNN credits, and thereby their actual impact on mitigating climate change, varies between the various credit types offered by the CNN.

Based on an analysis of forest carbon markets and changes therein, several options to use carbon credits in the refining and road transport sector have been explored. The forthcoming Concawe report shows that current policy conditions are not generally conducive to the use of voluntary carbon credits in the refining sector. The sector is covered by the EU ETS, and needs to obtain carbon emission allowances for the sector's total CO_2 emissions. Voluntary carbon credits could be purchased to offset residual emissions but they would not currently be recognised in the EU ETS.

A more promising option is to develop a 'zero carbon' or 'carbon neutral' petrol and/or diesel fuel for sale at retail stations. The sector would need to show that this fuel is made using best available technology (i.e. the most energy-efficient technology). Residual emissions could be offset with forest carbon credits. The price of offsetting these carbon emissions is almost the same for petrol and diesel, and is estimated (on the basis of well-to-wheel emissions) to range from 1.5 eurocent per litre (assuming a carbon price of 5 euros/tonne CO_2) to 3 eurocents per litre (on the basis of a carbon price of 10 euros/tonne CO_2). This product would, in line with 'green electricity' sold to households, probably not need fully separated supply chains as long as the sector commits to offsetting an amount of carbon equivalent to the carbon in purchased petrol. It is also important to demonstrate, in bringing this product to market, that the fuel is produced using best available technology, and that customers are offered the option of offsetting residual emissions.

Electric vehicles and 'carbon-neutral petrol' powered vehicles would have a very different environmental footprint. Their relative performance would be strongly influenced by how the electricity used to power electric vehicles is generated. A comparison would need to consider, among others, CO_2 and other emissions related to both electricity production and petrol and diesel use, and the environmental impacts of batteries during their life cycle.

Pending verification of the overall environmental performance of carbon neutral road transport, bringing carbon neutral petrol to market would offer a number of benefits including:

- offering consumers a carbon neutral product that is suited for people with driving requirements that cannot be met with electric cars;
- offering a low-cost, easy-to-implement option for compensating emissions from driving; and
- biodiversity conservation in tropical forests that would be conserved as a consequence of the use of carbon offsets.

Hence, carbon neutral petrol could bring substantial, low-cost benefits to both the industry and society in general, and the option needs to be studied in more detail and tested. Further steps required to bring the product to market include a basic life-cycle assessment to compare carbon neutral petrol and diesel powered cars to electric cars, working out the specifics of the carbon offsetting mechanism, development of a communication and marketing strategy, and piloting the approach in one or more countries. The forest carbon market is currently a buyer's market but this may change if the aviation industry continues with implementing the CORSIA initiative. The downstream sector should therefore consider evaluating the approach in the short term. If the sector decides to move ahead, access to carbon credits by working with carbon credit developers could then be obtained on the most favourable terms.

Validation of a simulation model for the assessment of CO_2 emissions of passenger cars under real-world conditions

The gap between real-world fuel consumption and manufacturers' figures has been increasing since 2001. Could the use of generic simulation models making use of on-road test data provide a more accurate approach to measuring fuel consumption and CO_2 emissions?

Background

Currently, European CO_2 emission and fuel economy targets for the automotive sector are based on the New European Driving Cycle (NEDC), a driving cycle that was not originally designed for this purpose. This has led to an increasing gap between the real-world average fuel consumption experienced by drivers and the respective type approval values reported by manufacturers. The divergence between real-world and type approval fuel consumption from 2001 onwards is depicted in Figure 1.

This gap is expected to decrease after the introduction of the new World-wide harmonized Light vehicles Test Procedure (WLTP), however, it will not disappear completely. One of the reasons for this is that the WLTP still covers only a limited area of the engine operating range, albeit a wider range than that covered by the NEDC. Consequently, it will still be possible for manufacturers to develop fuel economy measures applicable only within this limited engine operating range, and to follow different strategies outside of this range. It is therefore particularly important to explore the possibilities of using on-road test data and following a simulation approach to assess real-world CO_2 emissions, i.e. to cover the widest possible (if not the whole) area of the engine operating range.

The engine range covered during NEDC, WLTP and RDE is illustrated in Figure 2. It can be seen that, during an RDE test, contrary to NEDC and WLTP, a wider engine operating range is used.

Objectives

European regulation has already established RDE measurements for the evaluation of NO_x emissions from vehicles, providing the opportunity to expand this methodology to fuel consumption and the evaluation of CO_2 emissions, since current regulation covers only pollutant emissions and not CO_2.

Hence, this study investigates the possibility of evaluating real-world CO_2 emissions with generic simulation models, developed on the basis of portable emissions measurements system (PEMS) data and RDE recordings. The aim is to provide accurate and reliable CO_2 emissions simulations for any modern vehicle model, combined with RDE measurements. Additionally, the target is to further enhance the development of a methodology for the measurement and evaluation of real-world fuel consumption and CO_2 emissions. The final outcome could provide direction for further research into the development of a procedure that may be able to use RDE testing of CO_2 emissions for regulatory purposes.

Figure 1 Divergence between real-world and manufacturers' type-approval CO_2 emissions for various real-world data sources, including average estimates for private cars, company cars and all data sources [1]

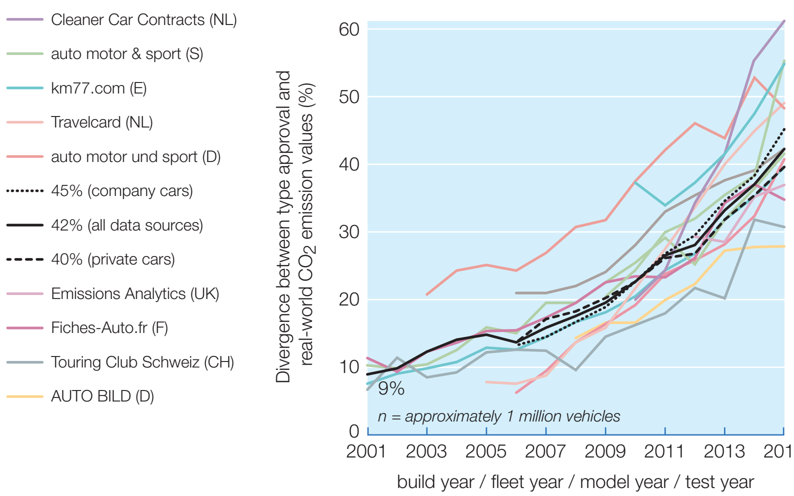
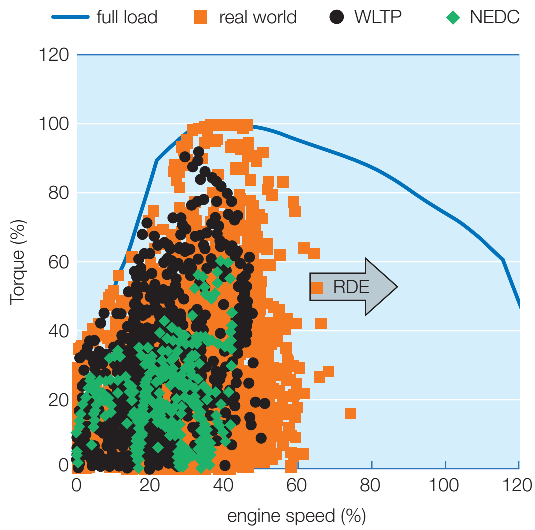


Figure 2 Engine operating range for NEDC, WLTP and RDE



Methodology

The procedure that was followed to develop a methodology for evaluating real-world CO_2 emissions using a simulation approach is summarised in the following steps and demonstrated in Figure 3.

As a first step, a validated vehicle model was used to specify and investigate the difficulties and limitations of such an approach. The real-world measurements are simulated with the existing model, which was built with input data derived by the respective OEM, and the results are compared against experimental data. These simulations provide some first indications of the difficulties and the limitations of the approach. At a second step, the same procedure is repeated for a new developed vehicle model with generic data, such as the engine map and the powertrain losses. In the third step, a comparison between the simulated CO_2 results for the two vehicle models is conducted, which highlights any differences among them, and indicates the parameters that need further calibration.

Simulation model

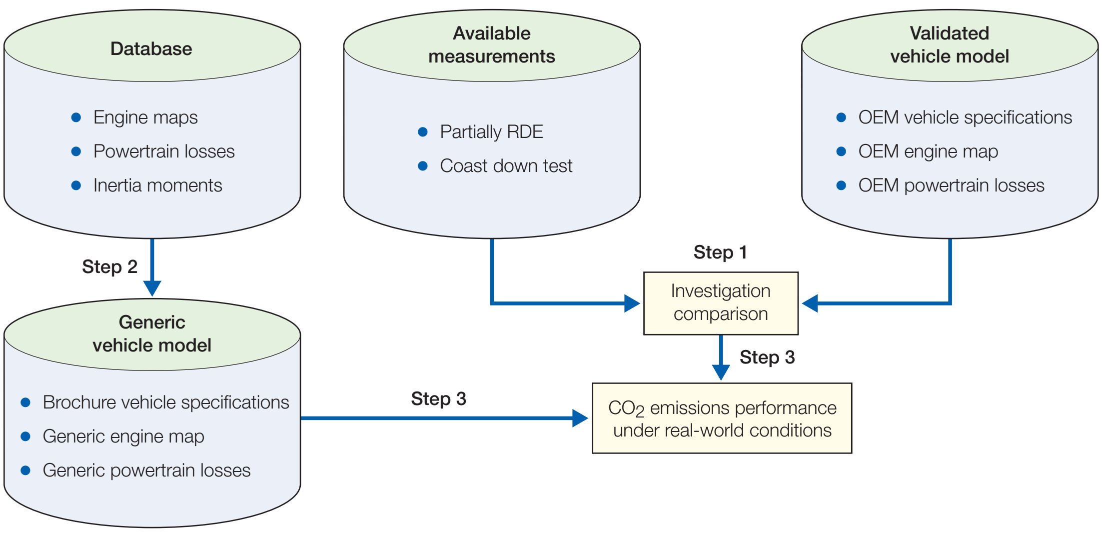
The aforementioned methodology was applied on a sport utility vehicle (SUV) equipped with a 2.0 litre diesel engine and 6-speed manual transmission. This vehicle is considered to be a mild hybridized Euro 5 passenger car, equipped with start-stop and brake energy recuperation features; its main specifications are summarised in Table 1.

Table 1 Vehicle specifications

Engine	diesel
Displacement (cc)	1995
Curb weight (kg)	1465
Maximum engine power (kW @ rpm)	120 @ 4000
Maximum engine torque (Nm @ rpm)	380 @ 1750
Gearbox	6-gear manual transmission
Tyres	225/50 R17
Emission standard	Euro 5
Type approval CO_2 emissions (g/km)	119

This vehicle was tested in facilities at the Laboratory of Applied Thermodynamics (LAT), Aristotle University of Thessaloniki, and a simulation model was developed and validated. All required data for the model was provided by the respective automotive OEM; hence it is considered as being an 'original model' of the vehicle. This model was calibrated and validated over cold and hot start NEDC and WLTP chassis dynamometer measurements; the

Figure 3 Schematic of the methodology

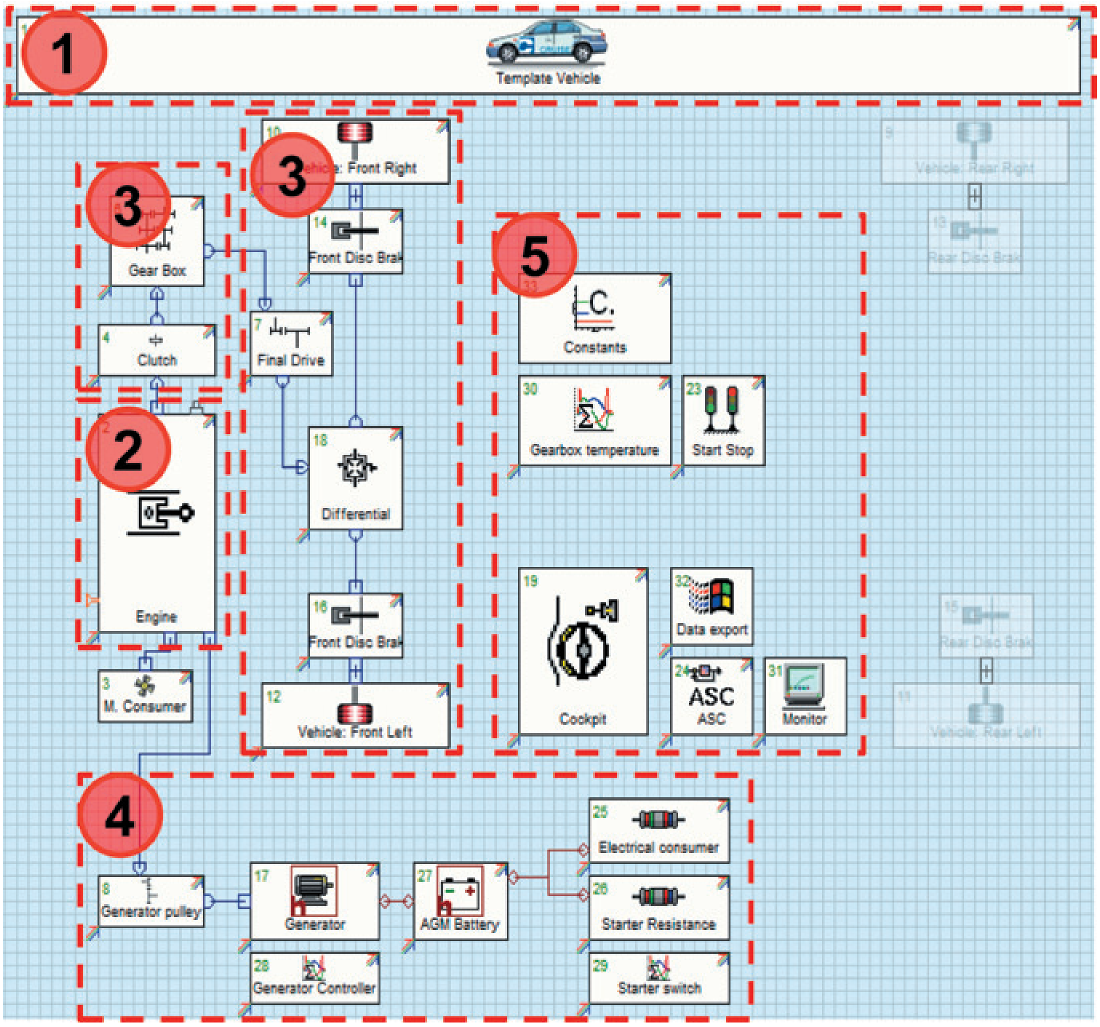


total error of the simulated fuel consumption for both cycles is below 1% compared to the measured value.

The commercial simulation platform, AVL Cruise™, was used to build the model and run the simulations. This is a micro-simulation tool used for emissions and powertrain analysis. It covers a wide range of vehicle types and is characterised by a fast calculation time with a multi-physics solver, as well as a modular and component-oriented modelling approach and onboard integration platform[2]. The graphical user interface of AVL Cruise™, together with the main vehicle components that were used for the simulations, is presented in Figure 4 and explained below:

- Component No. 1 describes the vehicle body, and is where information relevant to the test mass and the driving resistance coefficients are inserted as input.
- Component No. 2 describes the internal combustion engine, and is where the engine specifications (fuel, displacement, number of cylinders, etc.) for the simulated vehicle are inserted. Additionally this component also uses the fuel consumption (FC) map, the full load and the motoring curves.
- Component No. 3 (group of components) includes the drivetrain, and consists of the clutch, the gearbox, the final drive, the differential and the powered

Figure 4 AVL Cruise™ graphical user interface and topology for a conventional vehicle equipped with manual transmission and start-stop. The main vehicle components are highlighted.



wheels. The most important input parameters of this component are the gear and final drive ratios, the torque loss map of the drivetrain system and the dynamic radius of the tyres.

- Component No. 4, which consists of the generator and its pulley, the battery, the starter, and the electrical consumer unit along with their controllers, simulates the electrical system of the vehicle.
- Component No. 5 consists of the start-stop system together with other necessary modules essential for the simulation.

Measured data and model calibration

After the model had been completed, the next step was the validation of the model, which is based on data obtained with PEMS during real-world tests (including partial RDE measurements that were not fully compliant with the RDE regulation at that stage) held around the region of Thessaloniki, Greece.

The available instantaneous data from those tests include time, altitude and vehicle speed provided by the installed GPS, ambient temperature, engine load, battery voltage, engine coolant temperature, engine speed, intake air temperature, air flow rate, vehicle speed from the vehicle's on-board diagnostics (OBD) system and CO_2, CO, NO_2 and NO_x emissions from the PEMS instrument, while fuel consumption was calculated. The vehicle with the PEMS installation is shown in Figure 5.

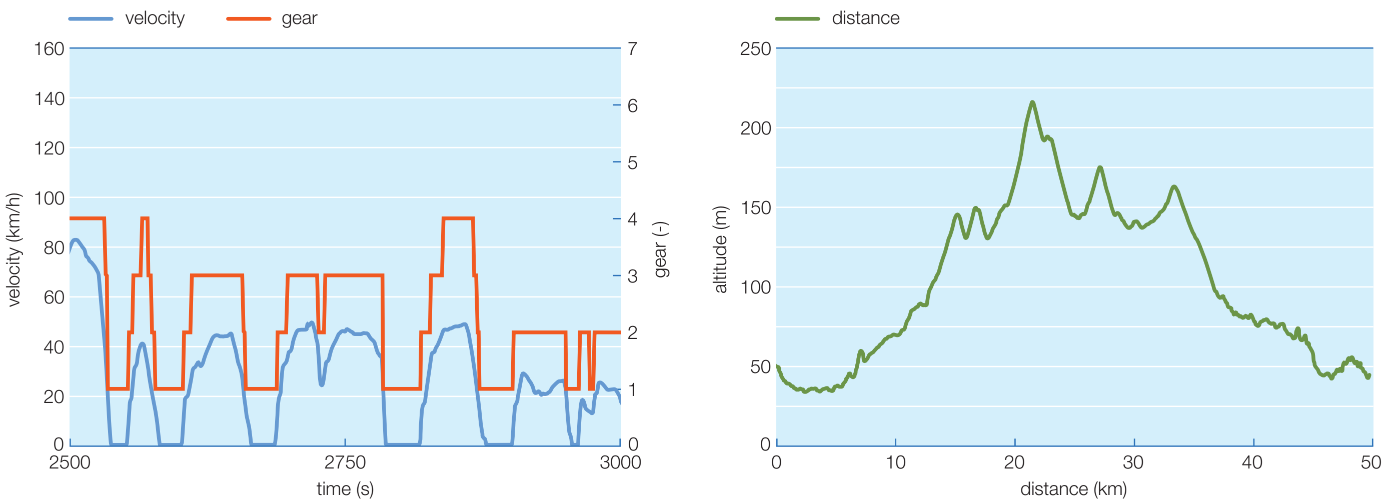
During the validation of the simulations, various parameters were used including time, altitude, vehicle speed from the GPS, engine speed from the OBD system and CO_2 emissions from the PEMS instrument, together with the calculated fuel consumption. For the determination of driving resistance, a coast-down test at a public site was performed. With regard to the alternator current, the measured signal from chassis dynamometer tests over WLTP was used (on-road measurements of alternator current were not included at that time). Alternator current during on-road testing can be also measured, thus the actual alternator's power consumption can be added to the simulation.

Figure 5 PEMS installation on the vehicle

The calibration of the model can be summarized in the following 5 steps:

- The first step involves the preparation of the gear shifting sequence as shown in Figure 6a on page 10. The selected gear versus time is calculated based on the total transmission ratio and engine/vehicle speed ratio.
- The second step is to use the altitude information from the trip, obtained using a GPS device (an example of altitude evolution as a function of distance can be seen in Figure 6b on page 10).
- The third step is to calculate the actual driving resistance of the simulated vehicle. This step is not required if a coast-down test is available. Otherwise approximations and assumptions based on the vehicle's geometry and specifications are conducted.
- The fourth step is to integrate the electrical model of the vehicle. At this point, the battery, alternator, starter motor and constant electrical consumption are added to the simulation.
- The fifth step involves evaluation of the simulation results. Simulated instantaneous engine speed, FC and CO_2 emissions are compared with the respective measurements.

Figure 6 Example of velocity, gear shifting and altitude



Internal database—generic model

The second step in this methodology is the development of a vehicle model with generic characteristics derived from LAT's internal database.

In the context of previous activities, LAT has developed a number of validated vehicle models using detailed necessary input data which were largely provided by the respective OEMs. This has led to the creation of an internal database, which consists of vehicle simulation models for 20 passenger cars and 3 light commercial vehicles (LCVs) equipped with manual or automatic transmissions. For the gasoline and diesel vehicles in the database, information related to fuel consumption engine maps, powertrain losses, inertia moments, gear shifting strategy and driving resistance coefficients are available from the respective OEMs. Figure 7 summarizes the contents of the database.

Using this database it was possible to derive generic engine maps, powertrain losses or powertrain efficiency maps, or to estimate the driving resistance coefficients. For example, diesel vehicles were divided into three clusters according to their displacement, as shown in Table 2 on page 11, and for each engine cluster one generic fuel consumption map was derived.

Figure 7 Contents of the LAT database

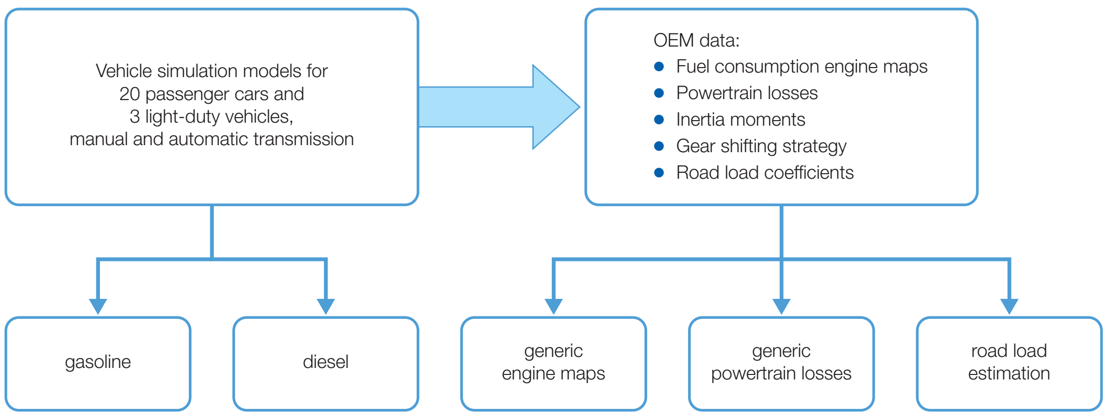


Table 2 Engine clusters

Engine cluster	Vehicle segment
1200–1400 cc	B, B, C
1500–1700 cc	C, MPV, SUV
1900–2200 cc	SUV, LCV, LCV

Simulation results

The outcome of the approach was the development of two simulation models, one with data provided from OEMs and one with generic data extracted from the internal database. The two models were used to calculate the CO_2 emissions performance for the same real-world driving velocity profile.

Figure 8 illustrates the measured (black line) and simulated (blue line) cumulative FC of the trip used in the simulation. The green line corresponds to the second-by-second difference between the measured and the simulated FC. The red dashed line is the 5% margin of the difference. Simulated FC does not include the altitude effect and, as a result, an underestimation is observed between 500 and 1500 seconds; this shows the importance of using accurate altitude recordings in simulation.

Looking into the instantaneous signals of the measured and simulated FC from 500 to 1000 seconds (see Figure 9) it can easily be seen that the measured signal is above the simulated signal for the given time period. However, areas where the measured signal is below the simulated one for the given time period are also present. This can be attributed to changes in the engine load caused by uphill and/or downhill driving.

After introducing the instantaneous altitude in the simulation, the calculated FC is seen to improve, and the underestimation between 500 and 1500 seconds is eliminated. The measured (black line) and simulated (with altitude effect) (blue line) cumulative FC data are presented in Figure 10. The slight constant overestimation in the simulated FC observed until 2500 seconds, may be attributed to driving resistance inaccuracies. Improvement of predicted FC is also observed in the instantaneous signals of the measured and simulated FC (Figure 11) where a good match between the two signals is indicated.

Figure 8 Measured and simulated cumulative fuel consumption, and the difference between measured and simulated fuel consumption
(altitude recordings are *not* included in the simulation)

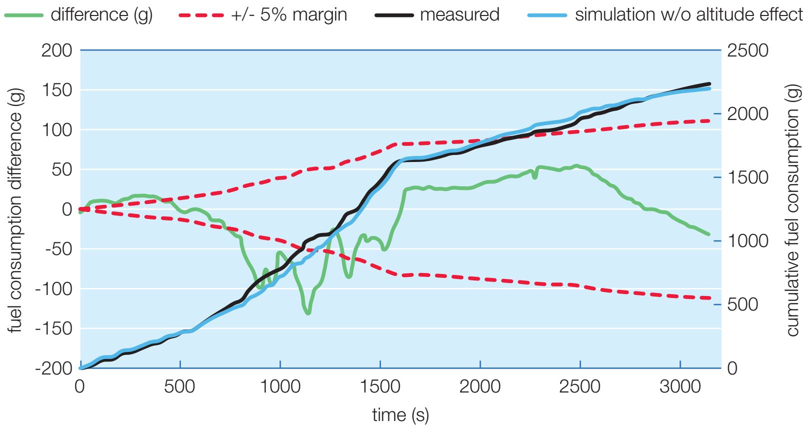


Figure 9 Measured and simulated instantaneous fuel consumption
(altitude recordings are *not* included in the simulation)

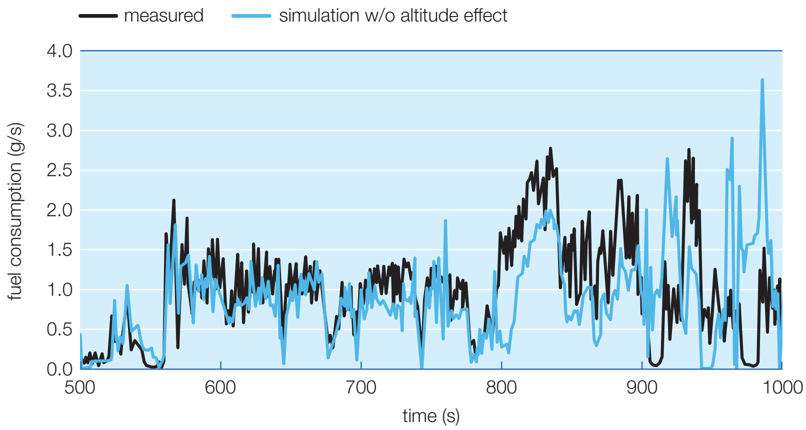


Figure 10 Measured and simulated cumulative fuel consumption, and the difference between measured and simulated fuel consumption
(altitude recordings *are* included in the simulation)

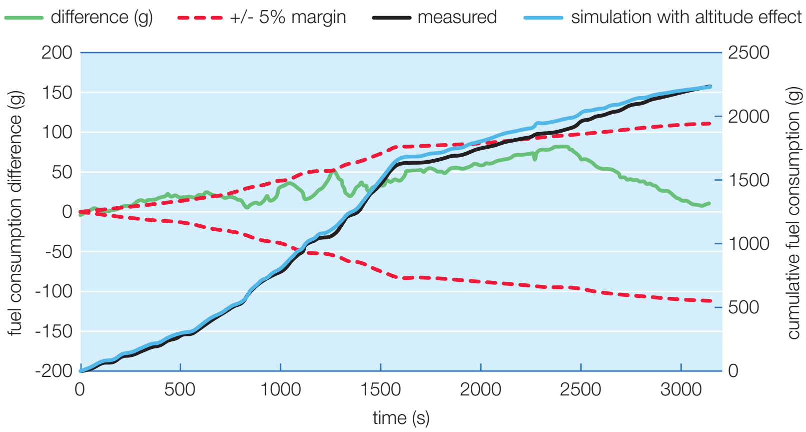
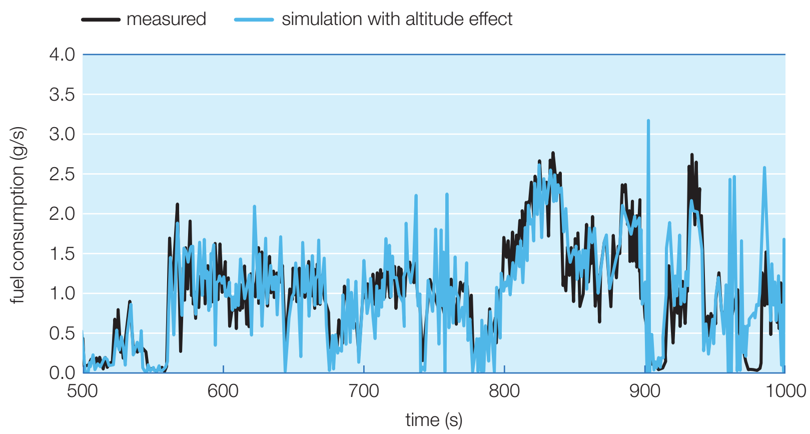


Figure 11 Measured and simulated instantaneous fuel consumption
(altitude recordings *are* included in the simulation)

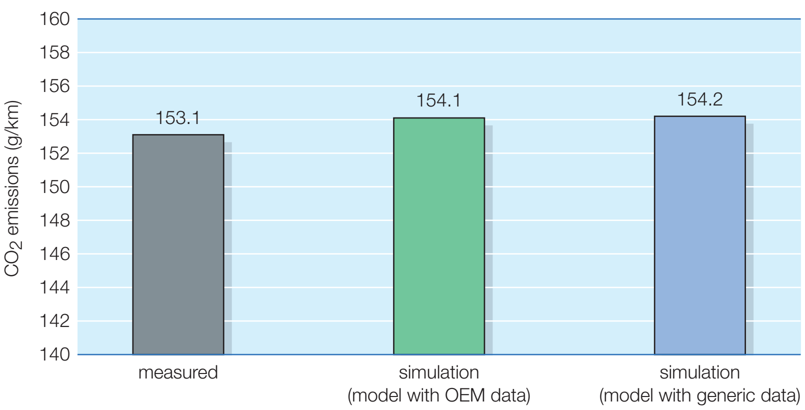


Finally, both models (i.e. the model with OEM data and the model with generic data) were used to predict FC and CO_2 emissions performance for the same measured trip. The total simulated CO_2 emissions results from the models are shown in Figure 12, compared with the measured value. From this comparison it can be seen that both models provide accurate results, only 1 g/km higher than measured.

The results of the simulation can be summarised as follows:

- The difference between measured and simulated FC remained within ±5% over the entire test.
- There was a slight overestimation of simulated FC for a small section of the test.
- The difference between measured and simulated total FC was less than 1%.

Figure 12 Simulated CO_2 emissions results compared with the measured value



Conclusions and future actions

The main objective of this study was to investigate the possibility of evaluating real-world CO_2 emissions with simulation models developed on the basis of portable emissions measurements system (PEMS) data and Real Driving Emissions (RDE) recordings.

During the analysis in this study, two simulation models were developed, one with data from the respective OEM and one with generic data extracted from LAT's database. For both models, CO_2 emissions and fuel consumption were simulated successfully and results from both models showed a good agreement with experimental data. The error in total simulated CO_2 emissions was lower than ±2.5%, and the cumulative fuel consumption calculated over the entire test remained within ±5%, compared to the measurements. The important outcome of the study is that a methodology to validate a simulation model for the assessment of CO_2 emissions under real-world driving conditions was drafted.

The results of the study provide a good basis for the rationale that could underpin a real-world based assessment of fuel consumption and CO_2 emissions and the development of a consistent methodology. However, an extensive investigation is required to cover all existing engine types (e.g. gasoline, both MPI and GDI, diesel, etc.), powertrains (e.g. manual and automatic transmissions, torque converter or double clutch systems) and vehicle segments (e.g. sizes, configurations and topologies, including hybrid systems, etc).

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Real-world emissions measurements of a GDI passenger car with and without a gasoline particulate filter

A new study aims to evaluate the effects of a gasoline particulate filter on NO_x and PN emissions from GDI passenger vehicles under real driving conditions.

Background

Emissions have been the focus of worldwide legislation for more than 25 years. Regulation initially concentrated on gaseous emissions of carbon monoxide, hydrocarbons and NO_x. However, particles emitted from vehicles and from other sources are now accepted as having an impact on air quality and on human health. Traditionally port fuel injected (PFI) gasoline vehicles generally emit very low levels of particulates because the fuel is well mixed with the intake air before combustion. Gasoline direct injection (GDI) vehicles have been increasing in market share due to their positive contribution to improving the average fleet fuel economy. GDI vehicles share some features with diesel vehicles in that the fuel is injected directly into the cylinder and has much less time to evaporate and mix before combustion starts, and this can lead to particulate formation [1].

Particle mass emissions are measured by collecting diluted exhaust gas on a filter paper which is then weighed to determine the amount of particulate. This method is effective even at the low Euro 5/6 levels, but the variability is such that small differences in emissions are difficult to detect. For this reason, a new particulate number (PN) test has been developed through the European Particle Measurement Programme (PMP) over the past decades and introduced from Euro 5 for both diesel and direct injection gasoline vehicles. A PN limit of 6×10^{11} particles/km became effective for diesel vehicles from November 2009, and this same limit will apply to direct injection gasoline cars from 2017 with an interim limit for the latter of 6×10^{12} particles/km which has been a requirement since 2014. Direct injection gasoline vehicles have so far met the limits through engine modifications [2] although the gasoline particulate filter (GPF) will be a practical approach to meeting future regulations as emission limits tighten further[3].

Emissions regulations for passenger vehicles have traditionally been based on the New European Driving Cycle (NEDC) run on the chassis dynamometer (rolling road). Amid concerns that this test cycle does not represent real road driving closely enough in terms of carbon dioxide (CO_2) and other emissions levels, two new test procedures are under development—the World-wide harmonized Light duty Test Cycle (WLTC) for use on the chassis dynamometer and, for on-road use, the Real Driving Emissions (RDE) test procedure. Included in the RDE test is the use of portable equipment measurement systems (PEMS) which are able to measure gaseous and PN emissions under real driving conditions. The RDE test protocol was adopted in 2016 together with a not-to-exceed limit (NTE) for NO_x. (NTE = conformity factor x limit value). Two extra Euro 6 stages will be introduced as a consequence, a temporary one as of September 2017 with a NO_x conformity factor[1] (CF) of 2.1 and a permanent one as of January 2020 with a NO_x CF of 1.5.

In parallel with the developments in vehicle technology, emissions regulation, measurement equipment and test cycles, the European Renewable Energy Directive (RED, 2009/28/EC) will require 10% renewable energy in transport fuels by 2020 while the Fuel Quality Directive (FQD, 2009/30/EC) will also require reductions in GHG emissions intensities from transport fuels of 6%. Oxygenated biofuels such as ethanol and ETBE, for example, are already used in Europe and their use is expected to increase to meet these regulatory demands. Reference fuels used for certification purposes have recently changed from E5 to E10 in moving from Euro 6b to Euro 6c specifications, and it is planned that RDE testing will be carried out on market fuels meeting the gasoline EN228 specification.

In a previous study[4], the Association for Emissions Control by Catalyst (AECC) and Concawe investigated the emissions from commercially available vehicles fitted with gasoline particulate filters under standard conditions, which concluded that the GPF could successfully reduce gasoline particulate emissions below the proposed limits. It was decided that it would be useful to measure real driving emissions on-road as well as simulated RDE on the dynamometer designed to go

[1] Conformity factor gives an indication of how close the measured value is to the limit value, i.e. CF = 1 means that the measured value = limit value.

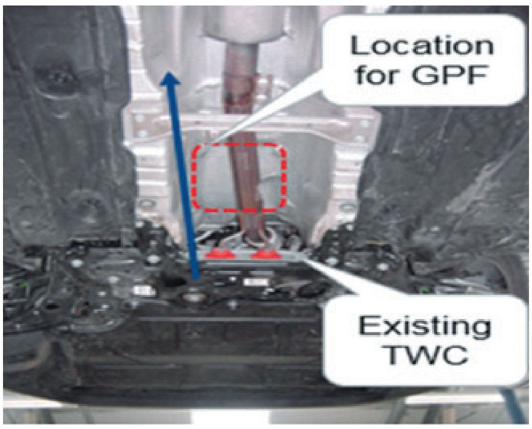
towards the limits of the RDE boundary conditions from a dynamic and temperature perspective (severitisation process). Fuel effects were also studied (this was not part of the previous study), and included tests on fuels representing the market and fuels with a range of qualities including E5 and E10. This article focuses on the dynamic (severity) test results. The low-temperature studies are described in a recently published SAE paper[5].

Test vehicle and modifications

The test vehicle was a direct injection 1.4 litre gasoline vehicle of Euro 6b specification, equipped with a three-way catalyst (TWC) for emissions control. This vehicle, as purchased, did not have a GPF but was retrofitted for the study so that GPF emissions could be measured before and after.

Chassis dynamometer tests were performed in the Vehicle Emissions Research Centre (VERC) of Ricardo UK. The vehicle was tested in both OEM build (without the GPF) and retrofitted with a GPF. To enable this, the baseline exhaust system of the vehicle was removed, and a straight section downstream of the existing TWC was cut out and replaced with the three-way catalytically-coated GPF.

Figure 1 Underfloor view of the test vehicle showing the unmodified exhaust system, and indicating the location for the GPF



Measurements and measurement systems

An important aspect of validating the performance of PEMS systems for on-road use is the correlation between PEMS and the laboratory-based analysers used during a WLTC test. This correlation must meet specified criteria that are laid down in the regulatory approach. All data shown in this paper are derived from compliant PEMS measurements, and validated not only during WLTC tests but also for dynamometer RDE tests.

By regulatory intent, on-road RDE tests are inherently variable, due to the unpredictable nature of traffic and the weather. However, to indicate the magnitude of this variability, three repeats of the on-road cycle were carried out, with testing occurring at the same time of day and using the same driver. The percentage variation in emissions levels, for all species of interest, derived from these three repeats were applied as error bars in the Figures presented in this article. For the on-dynamometer RDE tests, three repeats were conducted at one set of dynamometer loads (the loads most closely replicating the real road loads observed in the actual on-road RDE tests). With the elimination of traffic and weather variables, and despite the severitisation process, the on-dynamometer RDE tests showed improvement in repeatability when compared with the on-road tests. For example, the variation in CO_2 emissions from the baseline vehicle dropped from ~1.5% to nearer 1%.

Fuels and test matrix

Three fuels were tested, representing the certification fuel for Euro 6b (nominally RFE05), the certification fuel for Euro 6c (RFE10) and pump-grade gasoline currently available in the UK (EN228). Selected fuels data are shown in Table 1 on page 15.

The majority of the chassis dynamometer and RDE testing was conducted on the pump-grade fuel with a subset of tests conducted on the market EN228 (E5) fuel. Preliminary chassis dynamometer tests (NEDC and WLTC) were conducted on RFE05 for reference purposes and to relate emissions to those published from certification.

An overview of the tests, including chassis dynamometer, on-road and on-dynamometer RDE tests conducted after a 23°C soak and with a 23°C start temperature are given in Table 2.

The project commenced with an NEDC chassis dynamometer test, using the RFE05 fuel and the vehicle in standard build, to compare CO_2 and regulated emissions with certification levels and establish the effect of the road loads employed relative to the unknown certification loads. A WLTC test was also performed (without GPF) on this fuel. All tests were conducted at ~23°C including the overnight soak.

The vehicle was then equipped with a Horiba OBS-ONE PEMS system and the fuel was changed to pump-grade EN228. Single NEDC, WLTC and triplicate on-road RDE tests were conducted, both without and with the GPF. These tests were conducted at ~23°C including the overnight soak.

Following the chassis dynamometer and on-road tests on EN228, the fuel was changed to RFE10, and single NEDC, WLTC and triplicate on-road RDE tests, both without and with GPF, were carried out.

On-road Real Driving Emissions route

All on-road RDE tests were conducted on a route known to be EMROAD compliant with >10 vehicles (see Figure 2). EMROAD is the RDE validation tool which is used a part of the test procedure. Compliant routes contain equal amounts of urban, rural and motorway driving. This RDE route commences at the Ricardo site with immediate urban operation that is conducted wholly in 30 and 50 km/h zones within Shoreham-by-Sea. Increased urban severity is achieved through moderate hill climbs, inclusion of multiple T-junctions, traffic lights and a railway crossing so that no artificial stop periods are required. Rural and motorway sections are both out-and-back routes using roundabouts for the turn, with the rural section relatively flat and the motorway gradually ascending eastbound and descending on the westbound return trip.

Table 1 Selected fuel property data

	RFE10	RFE05	EN228
Density, 15°C (kg/m^3)	747.7	749.5	736.5
I.B.Pt. (°C)	37.3	35.6	24.6
% evaporated at 70°C, E70 (% volume)	43.8	32.8	47.3
% evaporated at 100°C, E100 (% volume)	57.1	56.1	61.6
% evaporated at 150°C, E150 (% volume)	90.4	88.2	92.7
% evaporated at 180°C, E180 (% volume)	-	95.2	99.0
F.B.Pt. (°C)	181.2	193.4	179.8
RON	97.4	95.5	96.8
MON	86.1	85.2	85.4
Aromatic content (% volume)	28.3	33.5	32.6
Sulphur content (mg/kg)	4.5	3.5	4.9
Atomic H/C ratio	1.799	1.845	1.861
Ethanol (% volume)	9.9	5	4.8

Table 2 Summary of 23°C start dynamometer and on-road tests

Exhaust	Fuel	NEDC + WLTC	RDE on road	RDE on dyno
Original (without GPF)	Ref E5	1x	-	-
	Ref E10	1x	3x	-
	Market E5	1x	3x	6x
With coated DPF	Ref E10	1x	3x	-
	Market E5	1x	3x	6x

Figure 2 Real Driving Emissions test route

Figure 3 PN emissions measured on the NEDC test cycle

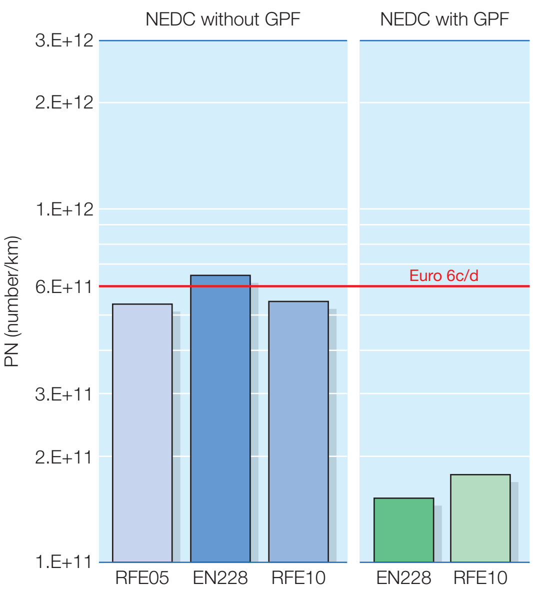
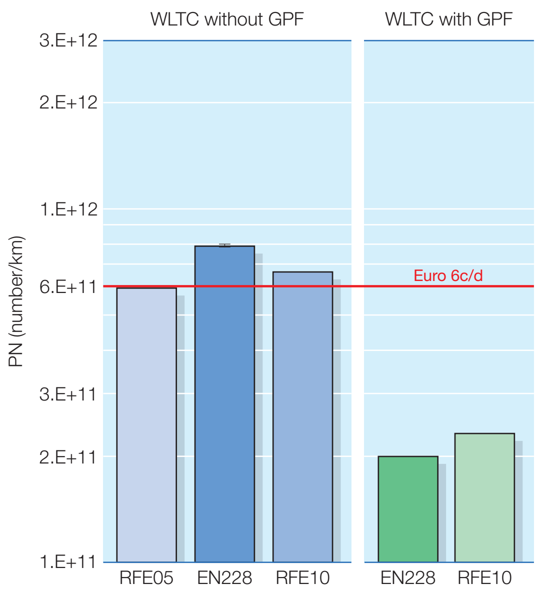


Figure 4 PN emissions measured on the WLTC test cycle

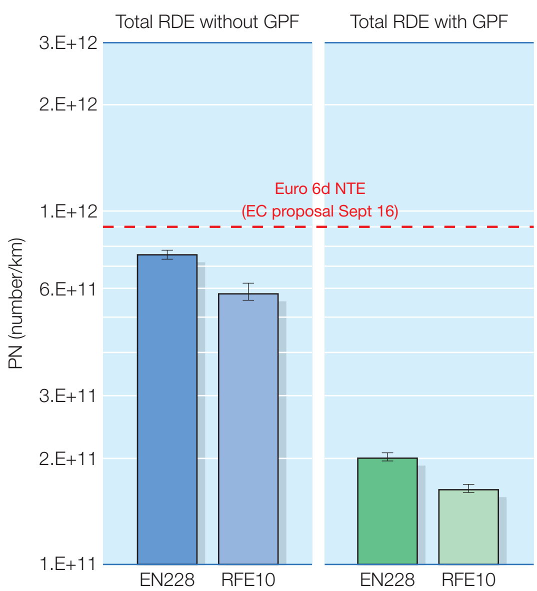


Particulate emissions under standard conditions

The PN measurements on the regulatory test cycles NEDC and WLTC (Figures 3 and 4, respectively) show that PN emissions on both cycles are just below the Euro 6c limit of 6×10^{11} particles/km for the reference E5 fuel. This confirms that, although the vehicle is type-approved according to the higher Euro 6b limit of 6×10^{12} particles/km, it is close to meeting the Euro 6c limit and it can be considered as state-of-the-art technology. PN emissions in the original configuration fluctuate around the Euro 6c limit; when considering tests on the other fuels as well, the variation is between 5.4×10^{11} and 7.9×10^{11} particles/km. For these tests it is difficult to draw conclusions on the differences between fuels due to the limited number of repeats, although directionally the WLTC results are higher than the NEDC results. All PN results with the GPF are significantly below the limit, between 1.5×10^{11} and 2.3×10^{11} particles/km across the two cycles.

PN emissions of the total RDE trip are plotted in Figure 5. PN limits need to be met, both for total PN emissions, as well as for PN emissions measured during the urban portion of the test cycle. Both total and urban results show a similar trend for the original vehicle configuration, but with different absolute levels. The highest PN emissions are observed for the urban part without GPF, being between 6.6×10^{11} and 8.9×10^{11} particles/km. The results are just within the Euro 6d NTE limit. This further confirms that the vehicle uses state-of-the-art GDI technology. With the GPF fitted,

Figure 5 PN emissions measured under total RDE



the PN results are below 6x10[11] particles/km, varying between 1.6x10[11] and 2.2x10[11] particles/km. There were some indications that, without the GPF fitted, PN emissions for the fuel containing 10% ethanol were lower than with the EN228 E5 market fuel. This was also reflected in the total RDE emissions with the GPF but not in the urban RDE PN emissions.

NO_x emissions under standard conditions

The NO_x emissions on the NEDC and WLTC test cycles were significantly below the Euro 6d limit on all fuels, for these laboratory cycles, without or with a GPF. No further NO_x reductions were observed from the coated GPF compared with those achieved with the TWC. The WLTC NO_x results are shown in Figure 6.

The NO_x emissions measured over the total RDE trip and the urban portion of the cycle are plotted in Figures 7 and 8. They are below the Euro 6 limit of 60 mg/km for all laboratory-based test cycles and well below the NTE limit for Euro 6d (shown). NO_x emissions during the urban part are higher than those over the entire trip. One test using the E10 fuel resulted in urban NO_x emissions of 59.7 mg/km, however, statistically there were no differences between the two fuels tested overall. The spread in NO_x emissions is lower with the GPF compared to the original vehicle configuration. Repeating the RDE test three times results in a spread for the urban NO_x emissions of between 27 and 60 mg/km without the GPF, and between 22 and 30 mg/km with the GPF. In contrast with the results of the regulatory test cycles, the coated GPF brings additional NO_x reductions in real-driving conditions.

Figure 6 NO_x emissions measured on the WLTC test cycle

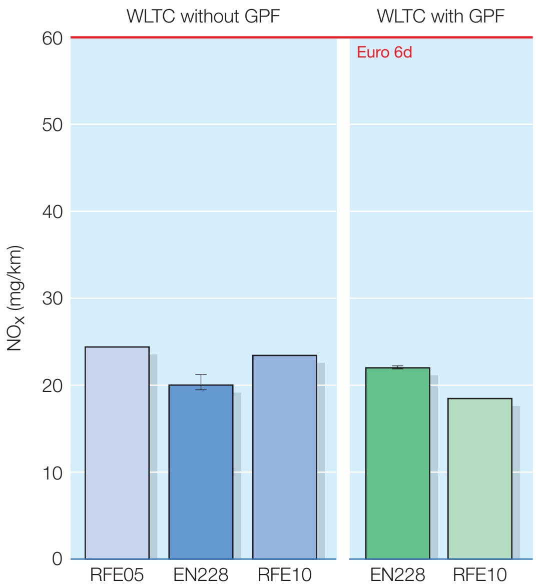


Figure 7 NO_x emissions over the RDE trip

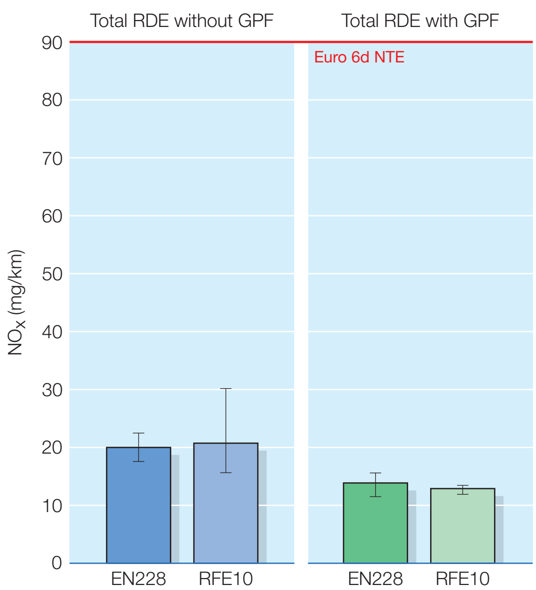
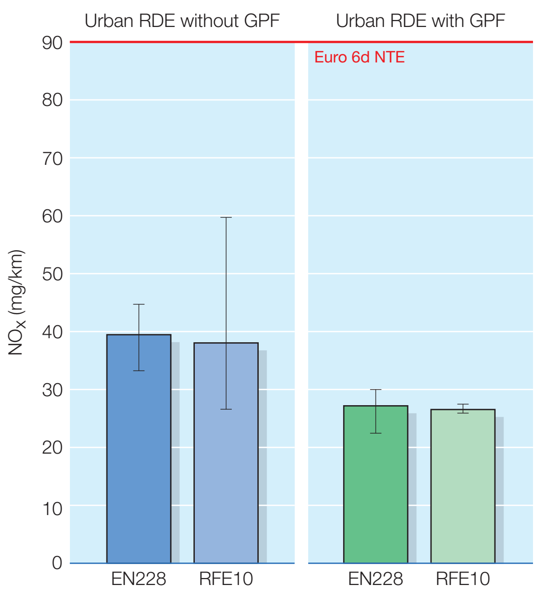


Figure 8 NO_x emissions over the urban part of the RDE trip



On-dynamometer RDE testing and results

Following completion of the NEDC, WLTC and on-road RDE tests using RFE10, the fuel was changed back to the EN228 market fuel and a process undertaken to develop three on-dynamometer RDE cycles with the aim of expanding the range of RDE test severities experienced by the test vehicle.

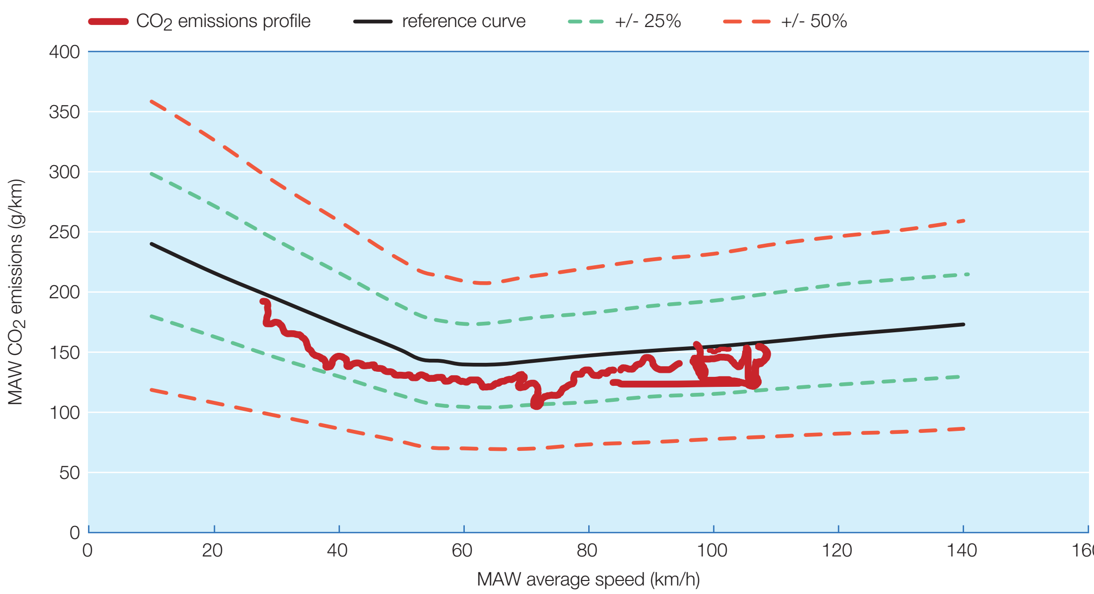
An RDE trip is defined by a number of boundary conditions defined within the regulation. Together these create a multidimensional RDE space within which a huge number of possible valid RDE routes exist. For certification purposes, a valid test is required on a single route only, but since this route may not present the most severe challenge possible within the RDE space, it was considered helpful to understand whether or not the GPF remains effective at higher RDE severities.

Within this programme, the CO_2 vs speed diagrams generated by EMROAD were used as the basis for defining severity, and an approach was developed to generate low, moderate and high CO_2 emissions for nominally the same vehicle speeds.

An on-road RDE test was selected as the basis for the on-dynamometer tests. The CO_2 speed diagram is shown in Figure 9. The 'characteristic' curve, which is generated from WLTC test data, increased to account for differences between certification road and real road loads, represents 'normal' operation. Low and high CO_2 validity limits are indicated by the dashed green lines, with each representing a 25% change in the normal levels. CO_2 emissions outside these levels are corrected by the EMROAD analysis up to the 50% boundary (dashed red line). Emissions beyond these levels are not taken into account. The objective was to create three RDE variants by aligning the measured CO_2 levels with the validity limits of EMROAD.

The speed vs time trace for the on-road RDE was entered into the chassis dynamometer driver's aid and the cycle driven. Luckily, the development of the RDE led to a CO_2 profile along the -25% validity line so this was adopted as the mild/low severity RDE (SRDE L). To generate RDE cycles that matched the characteristic curve (moderately severe RDE, SRDE M) and the +25% boundary (high severity RDE, SRDE H) it was necessary to increase the CO_2 without impacting the vehicle speed. This was achieved by determining a relationship between dynamometer load and vehicle CO_2. Required increases in CO_2, as percentages, were then calculated, and increments in acceleration and dynamometer loads required to move the CO_2 profiles up to SRDE M and SRDE H (see Figure 10).

Figure 9 CO_2 vs speed for the on-road RDE test cycle



The test vehicle was relatively low-powered, meaning that power/CO_2 was limited in the urban section. It was not possible to reach the '+25%' boundary in the urban section even though the vehicle was at full load, however it is clear that the most severe condition for CO_2 production in urban driving is being achieved in this case.

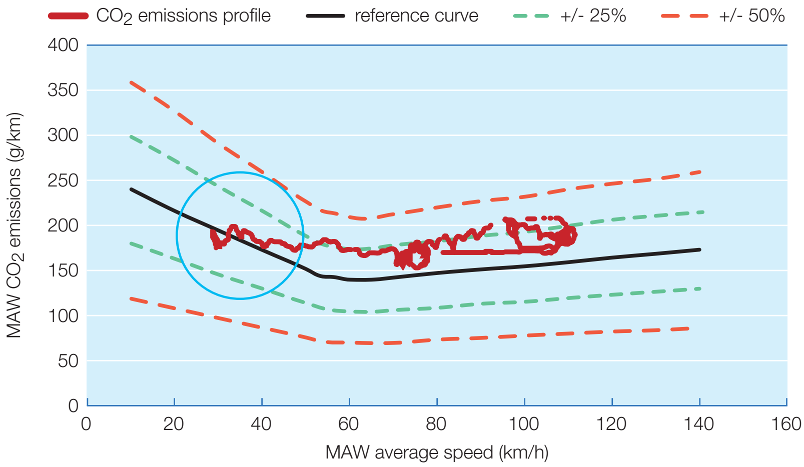
Using the EN228 market fuel, further RDE tests were carried out on the chassis dynamometer to explore the impact of the boundary conditions described above. The same trends can be observed for the evaluation of the total RDE trip or only the urban part. The highest absolute PN emissions are observed for the urban part.

The impact of vehicle acceleration and road load is shown in Figure 11 on page 20. The first bar in the graph gives the reference on-road result ('RDE road'). The second bar shows the on-dynamometer result of the same vehicle speed trace ('NRDE'), hence the difference between the first two bars indicates the impact of going from the road back to the dynamometer. PN emissions drop, as there is, for example, no road gradient when testing on the dynamometer. The following bars then show the results when a stepwise increase towards the RDE boundary conditions is taken. Comparing the bars labelled '1. SRDE L' and 'NRDE' shows the impact of increasing the acceleration with the severitised drive cycle. Without a GPF, PN emissions increase towards 2×10^{12} particles/km. With the GPF, the highest value is just above 5×10^{11} particles/km, remaining significantly below the NTE limit and also below 6×10^{11} particles/km.

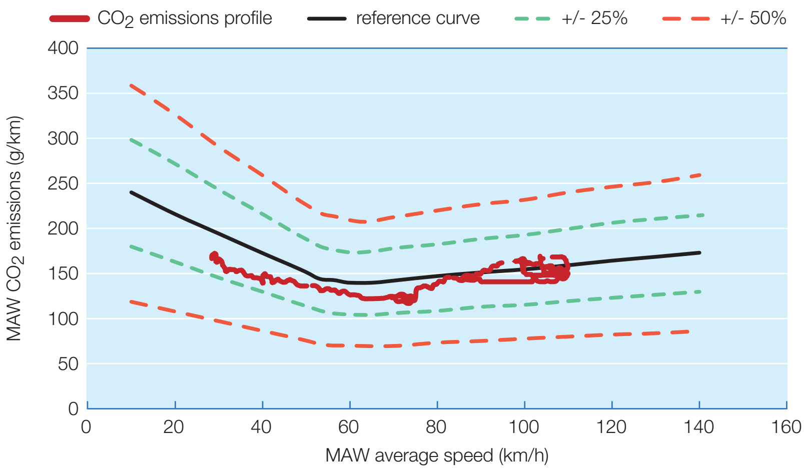
Figure 12 shows the impact of going towards the RDE boundary, and the effect of the severitised drive cycle (SRDE L) and increase in dynamometer load (SRDE M and SRDE H) on urban NO_x emissions. Without the GPF, NO_x emissions increase above 60 mg/km while with the GPF, the results stay below 60 mg/km. The total RDE NO_x results (not shown) also stay below 60 mg/km, test 2b being the highest at 40 mg/km without the GPF and 20 mg/km with the GPF.

Figure 10 CO_2 vs speed diagram showing SRDE on the +25% boundary, mid point and -25% boundaries respectively (SRDE H, M and L)

a) SRDE H (high severity)



b) SRDE M (medium severity)



c) SRDE L (low severity)

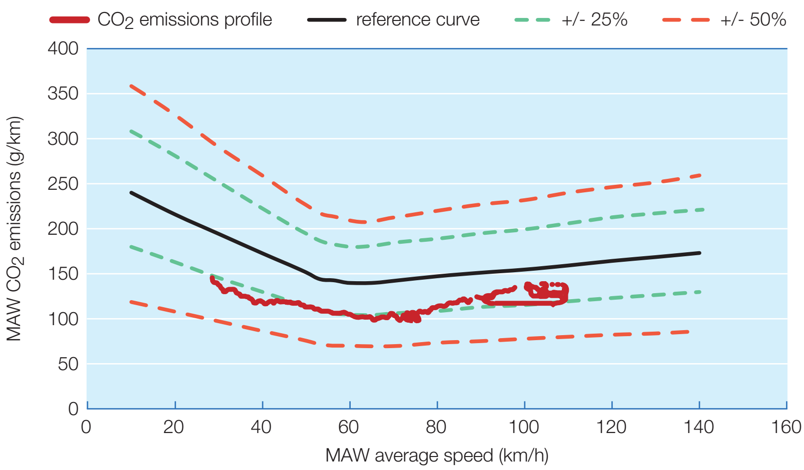


Figure 11 Urban RDE PN emissions measured on the dynamometer with increased vehicle acceleration and dynamometer load

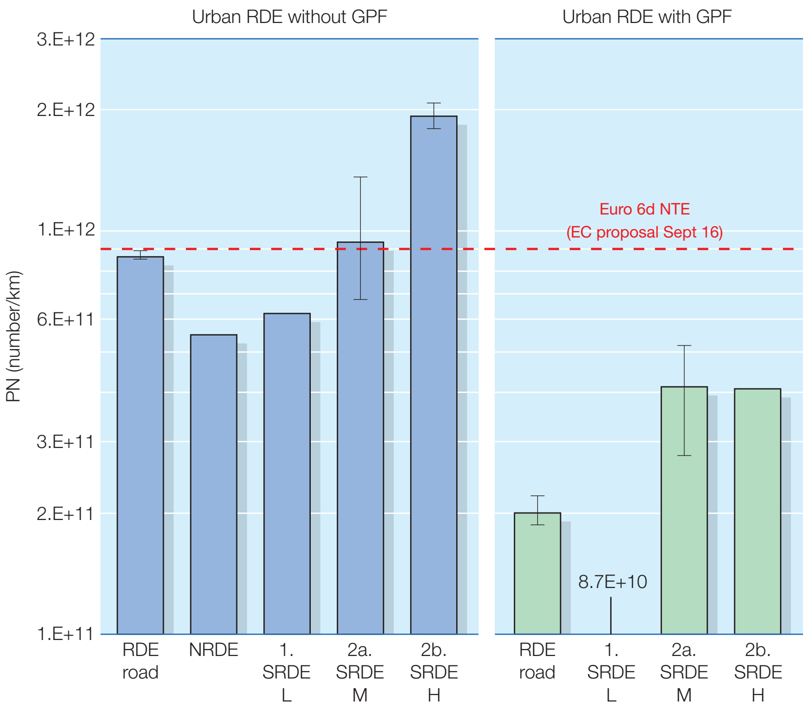
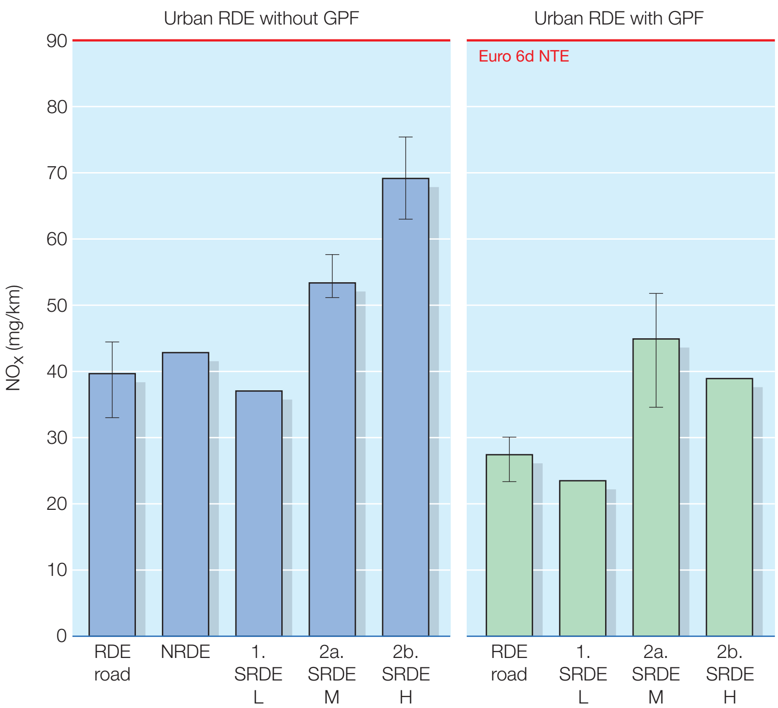


Figure 12 NO_x emissions during the urban part of the RDE trip measured on the chassis dynamometer



The use of a GPF reduces PN and NO_x

The study showed that, for a state-of-the-art GDI engine, PN emissions met the Euro 6c limit on the NEDC and WLTC regulatory test cycles. During the on-road RDE campaign, PN emissions were below the NTE limit. PN emissions of the vehicle without the GPF increased when vehicle acceleration, dynamometer load and ambient temperature were varied towards the boundary conditions defined within the RDE procedure. With the use of the GPF, PN emissions stayed below the NTE limit, even towards the RDE boundary.

NO_x emissions were always below the Euro 6d NTE limit in the original configuration throughout the tests. A further reduction in NO_x emissions was achieved with the coated GPF during real-world driving.

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Acknowledgments

This programme was funded by members of AECC and Concawe; test work was carried out by Ricardo, Shoreham-By-Sea, UK.

European cross-country oil pipelines

Monitoring the safety and environmental performance of Europe's oil pipelines

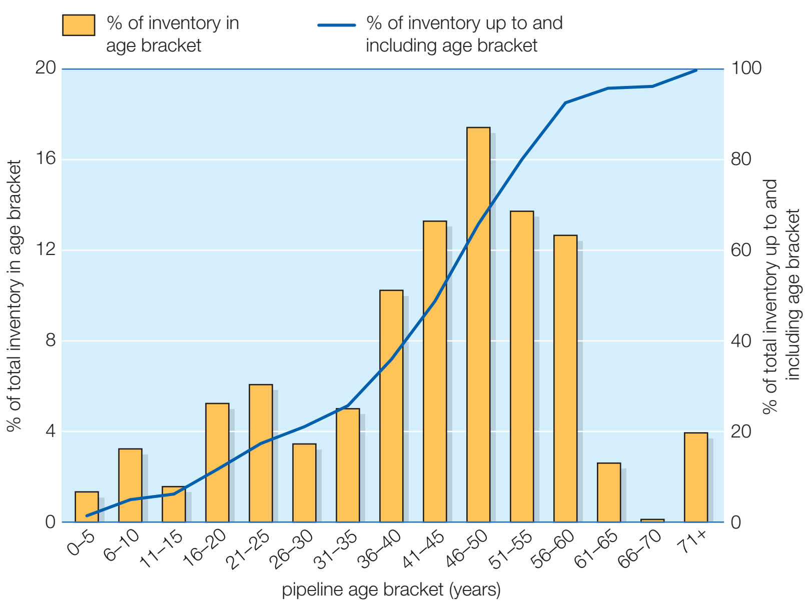
Introduction

The Concawe Oil Pipelines Management Group (OPMG) has collected data on the safety and environmental performance of oil pipelines in Europe since 1971. Information on annual throughput and traffic, spillage incidents and in-line inspection activities are gathered yearly by Concawe via on-line questionnaires. The results are analysed and published annually to show the yearly performance and also a full historical analysis since 1971, effectively creating an evergreen document updated every year. The following article provides an introduction to the content of the latest 2015 report, which can be downloaded from the Concawe website at www.concawe.be.

Concawe pipeline inventory

To date, Concawe has collected 45 years of spillage data on European cross-country oil pipelines. At nearly 37,500 km, the current inventory includes the majority of such pipelines in Europe, transporting some 751 million m^3 per year of crude oil and oil products. The 63 companies that reported in 2015 operate 141 pipeline systems split into 647 active sections running along a total of 33,903 km as well as 26 sections covering 2068 km which are currently (but not permanently) out of service.

Figure 1 European oil pipeline age distribution in 2015



When the Concawe survey was first performed in 1971, the pipeline system was comparatively new, with some 70% being 10 years old or less. Although the age distribution was quite wide, the oldest pipelines were in the 26–30 year age bracket and represented only a tiny fraction of the inventory. Over the years, a number of new pipelines have been commissioned, while older ones have been taken out of service. Although some short sections may have been renewed, there has been no large-scale replacement of existing lines. In 2015 4.6% of the total inventory was 10 years old or less, while 22,947 km (63.8%) was more than 40 years old. The 2015 age profile is shown in Figure 1.

The Concawe inventory data is a valuable resource for pipeline operators because it allows them to monitor trends in the causes of spill incidents and undertake remedial action at an early stage. In particular, it is important to identify any issues that are related to the age of the pipelines.

Historical analysis of spillages 1971–2015

Over the 45-year survey period, 489 spills have been caused by factors other than product theft, and the frequency of such spills has progressively decreased. In the past five years, however, the rate of incidence of product theft has increased considerably, leading to spills that are related to external factors rather than the condition of the pipeline infrastructure.

Several step changes in the inventory surveyed by Concawe over the years make the absolute spillage numbers difficult to interpret. The spillage frequency (number of spills per 1000 km pipeline, per year) is therefore a more meaningful metric. Excluding theft related spills, the 5-year moving average spillage frequency has reduced from around 1.1 in the mid 1970s to 0.17 in 2015 (Figure 2). When theft is included, however, the 2015 spillage frequency increases to 0.95.

Figure 3 shows the rapidly increasing trend in spillage incidents related to product theft from 2010 to 2015, and the importance of coordination between law enforcement agencies and pipeline operators to address this growing challenge. Since 1971, 186

Figure 2 45-year trend in spillage frequency (all pipelines, excluding theft)

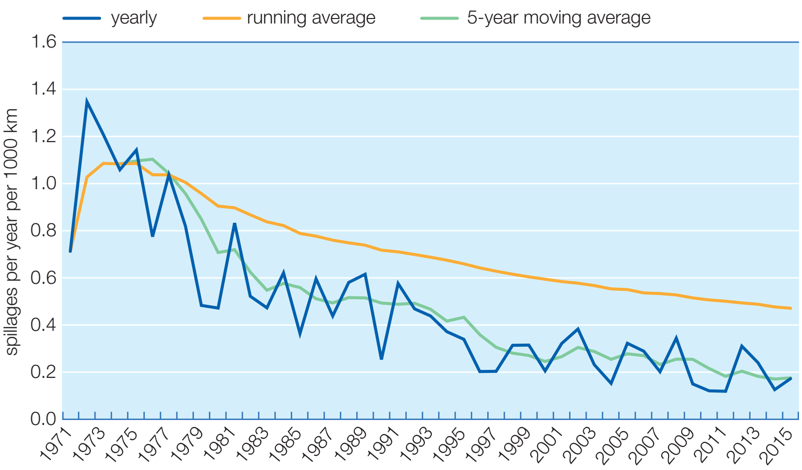


Figure 3 Evolution of the number of theft-related incidents since 2010

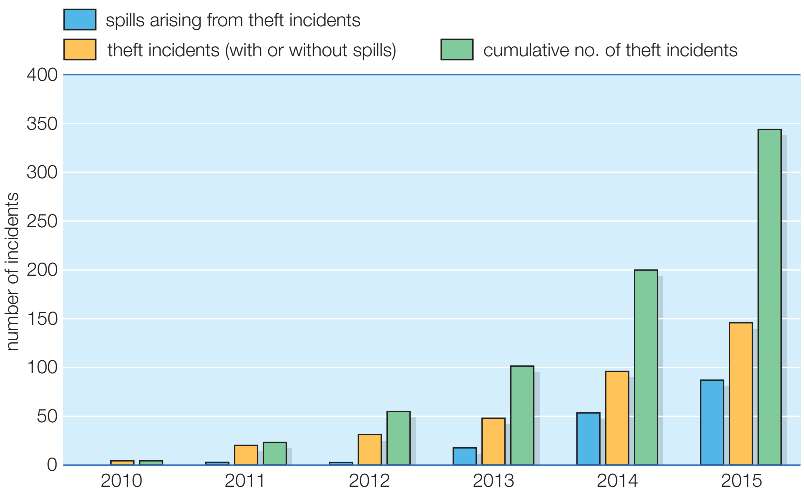
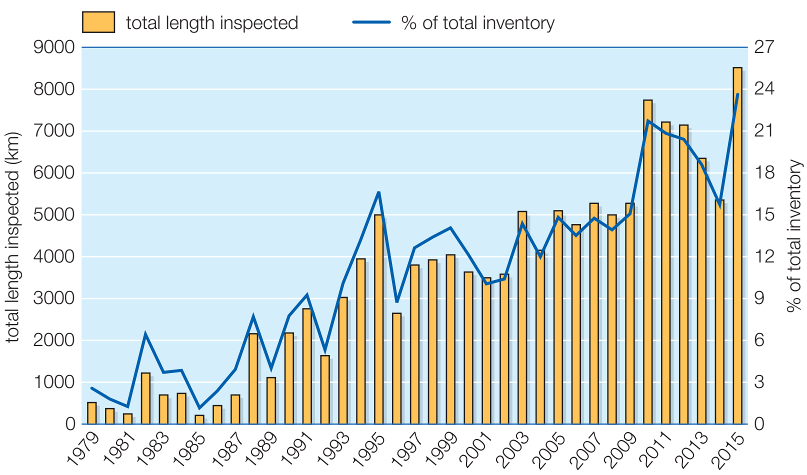


Figure 4 Total annual portion of the inventory inspected by inspection pigs



spillages have been caused by intentional damage by third parties, with 2 resulting from terrorist activities and 6 from vandalism. The remaining 178 were caused by attempted or successful product theft, and 158 of these were reported in the past three reporting years.

In-line inspection

The Concawe survey also collects summary data on in-line inspection activities undertaken by pipeline operators to detect any weaknesses in pipeline sections. Separate records are kept for metal loss, crack detection and for geometry (calliper) inspections. In 2015 the 63 companies who reported inspected a total of 93 sections with at least one type of inspection pig, covering a total combined length of 15,394 km. Most inspection programmes involved the running of more than one type of pig in the same section so that the total actual length inspected was less at 8,487 km (24% of the inventory).

As shown in Figure 4 the use of inspection pigs for internal inspection of pipelines grew steadily up to the mid-1990s, stabilising around 12% of the inventory every year. This further increased to around 15% in the first decade of the new millennium and reached 20% in the early years of the current decade. Following a short-term decline from 2010 to 2014, 2015 shows the highest figure ever recorded, resuming the long-term upward trend.

Summary

Analysis of 2012 to 2015 spill incident data shows that while the number of spill incidents due to product theft has greatly increased, the number of spillages associated with all other causes is continuing to decrease. In 2015, 6 reported spillages were due to causes other than product theft, corresponding to 0.17 spillages per 1000 km of pipeline. This is equal to the 5-year average and below the long-term running average of 0.47, which has been steadily decreasing over the years from a value of 1.1 in the mid 1970s. There were no reported fires, fatalities or injuries connected with these spills. In addition, 87 spillages were related to product theft attempts, which is a huge increase compared to the already high figure of 54 reported in 2014. Theft attempts caused a total of 28 spillage incidents between 1971 and 2012, and as many as 159 in the last 3 reporting years.

The annual Concawe survey was updated in 2016 to allow the collection of data on all theft incidents (irrespective of whether a spill took place). The first set of data from the new survey shows that a variety of connection techniques were used by the thieves and that in 10% of cases the pipeline was not breached. Automatic leak detection systems were able to detect 35% of the attempts, even though the abstraction flow rates were consistently under 1 m^3/h (suggesting that the thieves have an understanding of the operator's detection capabilities). Most connections were located in open countryside, with the collection point being close to the pipeline, although in 4% of cases the distance was in excess of 1 km. Storage facilities were reported in 20% of cases, however in only 12% of cases was this greater than 1 m^3.

Overall, based on the Concawe incident database and reports, there is little evidence that the ageing of the European pipeline system implies a greater risk of spillage. Analysis of 2012 to 2015 spill incident data shows that while the number of spill incidents due to product theft has increased, the number of spills associated with all other causes is continuing to decrease. The development and use of new techniques, such as internal inspection with inspection pigs, hold out the prospect that pipelines can continue reliable operations for the foreseeable future. Concawe pipeline statistics, in particular those covering the mechanical and corrosion incidents, will continue to be used to monitor performance.

Abbreviations and terms

AECC	Association for Emissions Control by Catalyst
ASC	Anti-Slip Control
C	Carbon
CDM	Clean Development Mechanism
CF	Conformity Factor
CNN	Climate Neutral Now initiative
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DPF	Diesel Particulate Filter
E5	Gasoline containing 5% v/v ethanol
E10	Gasoline containing 10% v/v ethanol
EMROAD	RDE validation tool developed by the Joint Research Centre of the European Commission
EN228	European Motor Gasoline Standard
ESR	Effort Sharing Regulation
ETBE	Ethyl Tertiary Butyl Ether
Euro 6	The European Commission's emission standards regulation for diesel vehicles
EU ETS	European Union Emission Trading System
F.B.Pt	Final Boiling Point
FC	Fuel Consumption
FQD	Fuel Quality Directive (2009/30/EC)
GDI	Gasoline Direct Injection
GHG	GreenHouse Gas
GPF	Gasoline Particulate Filter
GPS	Global Positioning System
H	Hydrogen
I.B.Pt	Initial boiling point
LAT	Laboratory of Applied Thermodynamics
LCV	Light Commercial Vehicle
LULUCF	Land Use, Land-Use Change and Forestry
MAW	Moving Average Window
MON	Motor octane number
MPI	Multi-Port Injection
MPV	Multi-Purpose Vehicle
Mt	Million Tonnes
NEDC	New European Driving Cycle
NGO	Non-Governmental Organisation
NO_x	Nitrogen Oxides (NO, NO_2)
NO_2	Nitrogen Dioxide
NRDE	Normal RDE
NTE	Not-to exceed
OBD	On-Board Diagnostics
OEM	Original Equipment Manufacturer
OPMG	Concawe Oil Pipelines Management Group
PEMS	Portable Emissions Measurement System
PFI	Port Fuel Injected
PMP	European Particle Measurement Programme
PN	Particle Number
RDE	Real Driving Emissions
RED	Renewable Energy Directive (2009/28/EC)
RPM	Revolutions Per Minute
RFE05, RFE10	Reference Fuels E5 and E10, respectively
RON	Research octane number
SUV	Sport Utility Vehicle
SRDE	Severitised RDE
SUV	Sport Utility Vehicle
TWC	Three-Way Catalyst
UN	United Nations
v/v	Volume to volume
VERC	Vehicle Emissions Research Centre of Ricardo, UK
WLTC	World harmonized Light duty Testing Cycle
WLTP	World-wide harmonized Light vehicles Test Procedure

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