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Effect of fuel on gasoline particulates emissions

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Gasoline particulate study

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ABSTRACT

Between 2019 and 2022, Concawe conducted a research programme examining the relationship between gasoline physical-chemical properties and particulate number (PN) emissions. The programme was executed in two distinct phases, during which 4 vehicles using 23 fuels were tested in emission laboratories equipped with a chassis dynamometer. All the combinations of vehicles and fuels tested showed tailpipe PN emissions compliant with the latest Euro 6d standards. For each phase, mathematical models were developed to examine the link between fuel properties and experimentally measured PN emissions.

The results from each phase are inconsistent with each other from a "fuel design" point of view. Additionally, it was not possible to predict the PN emissions of a given vehicle using the PN model elaborated from the other vehicle.

This suggests that it is difficult to identify a set of fuel parameters, which could be part of EN228, that would consistently decrease the PN emissions in all operations across all vehicles.

During the first phase, 13 formulated fuels (surrogates) were tested on a single vehicle equipped with a gasoline direct injection (GDI) engine and a gasoline particulate filter (GPF). The fuel matrix was designed to intentionally and independently vary different fuel properties suspected to impact PN emissions (according to the literature): volume evaporated at 150°C (E150) as a proxy of the heavy fraction of gasoline, total aromatics content, heavy aromatics content (more than 9 carbons) and ethanol content. The vehicle was tested using an "ambient start" (23°C) WLTC (Worldwide harmonized Light vehicle Test Cycle), a "hot start" WLTC and a test cycle simulating RDE (Real Driving Emissions) conditions. During the laboratory tests, both gaseous and particulate engine-out (EO) and tailpipe (TP) emissions were sampled. The particulate sampling included continuous PN10 and PN23 (PN having a diameter respectively bigger than 10 nm and 23 nm). In this first phase, it was concluded that it was possible to establish a fairly good and simple model between TP PN emissions and the fuel properties targeted in the fuel matrix, and more particularly E150 and total aromatics content. The experimental data was also used to check the correlation to other PN models referenced in the literature: "Honda PM Index", "Yield Sooting Index" (YSI), simplified PM index (based on E130 and E170) or a simple correlation with E150. It was found that none of these models correlate with the experimental data collected, showing the incapability of these literature models to actually predict PN emissions from the test vehicle on which they were not calibrated.

These two results demonstrate that, on one hand, it was easy to establish a simple model based on only two simple parameters such as E150 and total aromatics content; and on the other hand, it was impossible to find any correlation with any other existing PN models, including more complex ones. This conflict raised two fundamental questions on what was done during the first phase of the study:

- Would the models developed on the tested vehicle be valid on other vehicles?

- Would the models developed on the tested fuel matrix composed of surrogates be also valid on a fuel matrix composed of real market fuels?

These questions triggered the second phase of this study. This time, the study was conducted on three vehicles. Two of the studied vehicles were equipped with GDI technology (vehicles A and B), while the third one (vehicle C) was equipped with a

port fuel injection (PFI) engine. All of them were equipped with GPFs. Eight market fuels, sampled from European refineries, were tested on each of the vehicles. The fuel matrix was designed to vary different fuel properties such as E150, total aromatics and olefins content or ethanol content by targeting specific samples in the refineries, but without any specific intervention in the fuel design. Additionally, two fuels had to be specifically formulated to complete the fuel matrix, reaching a total of ten fuels. The range of variation of the fuel properties was selected to match the values seen in the EU FQD market survey[1]. This second phase followed a similar structure as the first one:

- an experimental part for the purpose of vehicles testing with an experimental setup similar to the first phase (using a different RDE cycle and with a cold start at 12°C to be representative of average real-world conditions in Europe)

- a modelling part, focused mainly on relationships between fuel properties and PN emissions with a specific part on vehicles cross-comparisons regarding their fuel response.

In the second phase, a relatively great variation in how the different vehicles responded to the fuel properties was observed. The magnitude of PN10 EO emissions for the two GDI vehicles were found relatively similar, and the PFI equipped vehicle, vehicle C, produced lower PN10 EO emissions. However, the magnitude of PN23 EO emissions was found similar between vehicles A and C and the PN23 EO emissions were significantly higher for the second GDI vehicle (vehicle B). Furthermore, the filtration efficiency of vehicle A's GPF was found fairly high, resulting in extremely low PN TP emissions overall. This was not as much the case for vehicle B, which produced higher PN TP emissions compared to the other two test vehicles. Although the PFI vehicle (vehicle C) was also equipped with a GPF, vehicle A still produced lower PN TP emissions although GDI technology is typically expected to produce more PN emissions than PFI technology. In an attempt to better understand the potential impact of the fuel properties on GPF's filtration efficiency, correlations between EO and TP emissions were studied as a function of fuels. Unfortunately, this showed no consistent response, as some fuels increasing the EO PN emissions could decrease the TP PN emissions, and vice-versa. Furthermore, in order to improve the understanding of the fuel response of the three test vehicles, the correlation between each vehicle's PN emissions was also studied. It showed that there was no correlation between the PN emissions of the three test vehicles. It means that each vehicle's PN emissions react differently (and sometimes in opposite directions) to a given modification of fuel physical-chemical properties. These observations have important consequences: they imply that it is not possible for the fuel producer to design a fuel that simultaneously reduces the PN emissions in all vehicles.

With the direct data collected, no accurate fuel-related modelling was possible due to strong temporal trend behaviour of PN emissions for vehicles A and C. For these vehicles, it was observed that the PN emissions measurements of the reference fuels shifted over time throughout the test campaign. For this reason, the data was corrected by normalizing against repeat of the reference fuel to (successfully) improve the results repeatability. Despite effective corrections were applied, relatively large error or noise for some of the PN data remained. Vehicle B was found to be less subject to measured temporal deviation and more repetitive throughout the test campaign. The most significant PN influencing factors found during the analysis for vehicle B were aromatics content and vapour pressure

[1] see ETC CM products — Eionet Portal (europa.eu)

(DVPE), which were found to increase PN emissions, while fuels with a lower yield in the early distillation curve (IBP to 50% vol) or a lower E70 tend to decrease PN emissions (or in other words, fuels having a bigger light fraction tend to increase vehicle B's PN emissions). For Vehicle A, similar conclusions were drawn for PN23 EO, but no satisfying model could be obtained for PN TP nor for PN10 EO. For vehicle C, the correlations were poor and the effect of fuel properties on PN emissions could not be identified. PN values without prior calibration of the model on these measurements. Overall, the PN models created for vehicles A and C were found inaccurate while the PN models generated for vehicle B resulted in relatively robust and accurate output.

During the comparison of the PN models generated for each vehicle, it was found that a relatively accurate PN model could be obtained specifically on vehicle B, however, this model does not fit with the results of other test vehicles. This is mostly due to differences in the vehicle specific fuel response, e.g., because of the characteristics of vehicle injection technology, strategy and GPF filtration efficiency that greatly impacts the outcome of PN TP emissions. As a result, any vehicle-to-vehicle cross-modelling was found to be inconsistent (within vehicles of Phase 2, tested in the same conditions, and also across vehicles of the first and second phase, tested in different conditions).

Overall, in answer to the two questions from Phase 1, it was impossible to design a consistent TP or EO PN model based on fuel properties across the different vehicles and powertrains. However, it was possible to elaborate individually accurate PN emissions models based on the fuel properties for two of the vehicles tested in the whole test programme (phase 1 and 2 together), but it was impossible to obtain any satisfying model for the two other vehicles. It is noteworthy that the two vehicles for which it was possible to elaborate PN models are different, tested in slightly different driving conditions, but made by the same OEM and equipped with the same engine. The models obtained on each of these two vehicles are significantly different: while they both indicate that an increased content of aromatics tends to increase PN emissions, one of the models indicates a stronger correlation with the high boiling end of the distillation curve, conversely the other model indicates a stronger correlation with the light end of the distillation curve.

KEYWORDS

Particulate number emissions, Gasoline, Gasoline Direct Injection, Port Fuel Injection, Gasoline Particulate Filter, Distillation curve, Aromatic content

INTERNET

This report is available as an Adobe pdf file on the Concawe website (www.concawe.org).

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Abbreviations

CNC -	Condensation Nucleation Counter
CO -	Carbon monoxide
CO2 -	Carbon dioxide
CVS -	Constant volume sampling
EATS -	Engine after treatment system
EFM -	Exhaust flow meter
ELPI -	Electrical Low-Pressure Impactor
EO -	Engine out
FTIR -	Fourier-transform infrared spectroscopy
FQD -	Fuel Quality Directive
GDI -	Gasoline direct injection
GPF -	Gasoline particulate filter
NMHC -	Non Methanic Hydrocarbons
NOx -	Nitrogen oxides
OBD -	On board diagnostics
PFI -	Port fuel injection
PM -	Particle mass
PN -	Particle number
RDE -	Real Driving Emissions
THC -	Total hydrocarbon content
TP -	Tail pipe
TWC -	Three-way catalyst
WLTC -	Worldwide harmonized Light vehicle Test Cycle
WLTP -	Worldwide Harmonised Light Vehicle Test Procedure

SECTION 1

OVERARCHING INTRODUCTION

1. OVERARCHING INTRODUCTION

The scope of this report is to examine the relationship between gasoline physical-chemical properties and particulates number (PN) emissions. PN emissions have become a topic of concern for the health authorities in the recent years, and more particularly regarding the smallest particulates that are suspected to be harmful to the human body as they could penetrate deeper into the vascular system. This has been translated into the Euro 6 standards for spark-ignited (gasoline) engine-equipped vehicles, where PN emissions having a diameter bigger than 23 nm have successively been limited to 6.10^{12} #/km and then to 6.10^{11} #/km. For the future, the draft Euro 7 regulation considers smaller particulates, bigger than 10 nm, still limited to 6.10^{11} #/km.

In this context, the auto industry has worked on several means to reduce PN emissions of petrol engines to meet the emissions standards, and more particularly those of gasoline direct injection (GDI) engines that are usually identified as higher emitters: engine design (e.g. injector location and fuel spray targeting), engine calibration (e.g. injection phasing, number of injections), injector design (e.g. injection pressure, spray formation) and aftertreatment systems (e.g. gasoline particulate filter (GPF)). As the Euro 6 standard introduced real driving emissions (RDE) testing, where vehicles are tested on-road with any market-compliant fuel (evolving from the previous Euro standards where vehicles were tested in lab conditions – chassis dyno – with homologation fuels having a narrow specification), it was quickly observed that the fuel physical-chemical properties could impact the PN emissions. This triggered a new field of research, consisting in identifying the influence of fuels physical-chemical properties on PN emissions (and as complementary means to reduce PN emissions), which is also the scope of this report.

The present report reviews the results obtained during three years of research activities that were conducted in two distinct phases:

- During the first phase, 13 formulated fuels (surrogates) were tested on a single vehicle equipped with a GDI engine and a GPF. The fuel matrix was designed to intentionally and independently vary different fuel properties suspected to impact PN emissions (according to the literature): volume evaporated at 150°C (E150) as a proxy of the heavy fraction of gasoline, total aromatics content, heavy aromatics content (more than 9 carbons) and ethanol content. The content of this phase was divided into two main parts: an experimental part where the vehicle was tested in an emission laboratory equipped with a chassis dynamometer; and a second part that was solely based on mathematical modelling, where the experimental results acquired from the first part were used for further analysis and model development. The main objective of the modelling was to find relations between fuel properties and PN emission formation.

- During the second phase, tests were conducted on three vehicles. Two of the studied vehicles were equipped with GDI technology (vehicles A and B), while the third one (vehicle C) was equipped with a port fuel injection (PFI) engine. All of them were equipped with GPFs. 8 market fuels, sampled from European refineries were tested on each of the vehicles. The fuel matrix was designed to vary different fuel properties such as E150, total aromatics and olefins content or ethanol content by targeting specific samples in the refineries, but without any specific intervention in the fuel design. Additionally, 2 fuels had to be specifically formulated to complete the fuel matrix, reaching a total of 10 fuels.

This second phase followed a similar structure as the first one: an experimental part for the purpose of vehicles testing, with an experimental setup similar to the first phase (using a different RDE cycle and with a cold start at 12°C to be representative of average real-world conditions in Europe); and a modelling part, focused mainly on relations between fuel properties and PN emissions, with a specific part on vehicle cross-comparisons regarding their fuel response.

To review the obtained results from this study and the conclusions that can be drawn from them, this report is structured in five sections as follows:

- Section 1 is an overarching introduction to the whole study;
- Section 2 relates to the first phase of the gasoline particulate study only, and can be read as an independent report;
- Section 3 explains how the first and the second phase of the study are interrelated, and more particularly how the conclusions obtained at the end of the first phase triggered the second phase;
- Section 4 relates to the second phase of the gasoline particulate study only, and can also be read as an independent report;
- Section 5 is an overarching conclusion to the whole study, encompassing the insights learnt from the first and the second phase.

SECTION 2

GASOLINE PARTICULATE STUDY - PHASE 1

2. PHASE 1 - INTRODUCTION

The purpose of the Phase 1 of the gasoline particulate study is to examine the relationship between gasoline physical-chemical properties and particulates number (PN) emissions. This study was commissioned by Concawe and Aramco Overseas Company (AOC). The study was executed by CERTAM for the experimental portion and by PHS Consulting for the modelling portion.

During the first phase, 13 formulated fuels (surrogates) were tested on a single vehicle equipped with a GDI engine and a GPF. The fuel matrix was designed to intentionally and independently vary different fuel properties suspected to impact PN emissions (according to the literature): volume evaporated at 150°C (E150) as a proxy of the heavy fraction of gasoline, total aromatics content, heavy aromatics content (more than 9 carbons) and ethanol content. The content of this phase was divided into two main parts: an experimental part where the vehicle was tested in an emission laboratory equipped with a chassis dynamometer; and a second part that was solely based on mathematical modelling, where the experimental results acquired from the first part were used for further analysis and model development. The main objective of the modelling was to find relations between fuel properties and PN emission formation.

3. PHASE 1 - EXPERIMENTAL SETUP

3.1. ROLLING TEST BENCH FACILITIES

The tests were performed on a chassis dynamometer, property of IRSEEM Technological Centre. The test facility is a full HORIBA installation, controlled by STAR VETS operating system, and meets Euro 6d regulatory requirements for gasoline and Diesel vehicles.

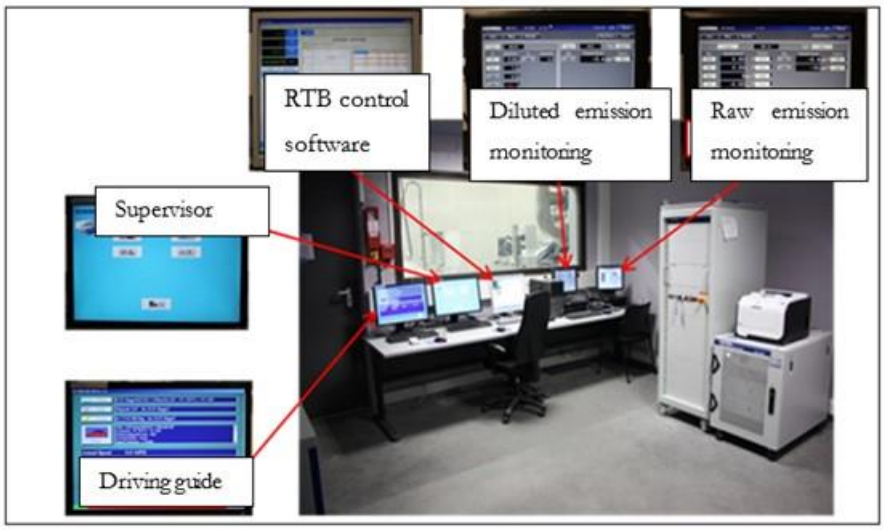


Figure 3.1 Rolling test bench (RTB) control cell

The general key elements of its technical definition are reported below:

- 2WD/4WD capability
- Temperature range: 14°C to 30°C (+/- 1,5°C)
- Hygrometry regulation: 45% (+/-5%)
- Dynamical road slope capability
- Maximal speed: 200 km.h-1
- Maximal speed of air: 130 km.h-1
- Oven and weighting devices for GPF/DPF soot measurement

Figure 3.2 Rolling Test Bench Cell

3.2. REGULATED EMISSIONS MEASUREMENT

A HORIBA system runs the gas analysis. The main characteristics of this system are given below:

- Dilution:
    - Gasoline and Diesel dilution tunnels
    - CVS-7400S HORIBA, gasoline and Diesel
- Diluted emissions:
    - Device HORIBA MEXA-7200H HORIBA
    - Continuous measurements: THC, CH4, CO, CO2, NO, NOx.
    - 4 bags WLTP compliant
    - Particle Number by 2300SPCS (>23nm)
- Tailpipe and engine-out emissions:
    - Device MEXA-7500DEGR HORIBA.
    - Continuous measurement THC, CH4, CO, CO_2, NO, NOx, and O_2.

In addition, fuel consumption is calculated by carbon balance from diluted gas measurements during the tests (global WLTP and RDE cycles, or by phase).

3.3. TEST VEHICLE – EXHAUST LINE INSTRUMENTATION

The tested vehicle was a Peugeot 308 GT Line equipped with an EB2DTS GDI engine (1,2 L displacement – "PureTech130 S&S") and a GPF. Further details about the engine characteristics are provided in the table below. The engine break-in was performed on open roads during approximately 7000 km. The first fill engine lubricant 0W20 grade was used (Total Quartz Ineo) and the level was checked before each test. No oil fill was needed during the period of experiments.

***Table* 3.1** Detailed engine characteristics

Engine Specifications		PureTech 110 S&S / PureTech 130 S&S
Type		*3 cylinder, in-line*
Emissions level		*Euro6d temp*
Fuel consumption on 308	*g C02/km*	*Approval in progress according*
Max. power	*kW/hp*	***96 / 130** at 5,500 rpm* ***81 / 110** at 5,500 rpm*
Max. torque	*Nm*	***230** at 1,750 rpm* ***210** at 1,500 rpm*
Combustion type		*Turbocharged central direct-injection engine* *Variable intake and exhaust setting*
Engine management and fuel intake		*SSTG PSA command-control system* *Direct injection 250 bars*
Electric management		*Smart power management with optimisation of battery charge and Stop & Start*
Engine displacement	*Cm3*	*1,199*
Compression ratio		*10.5: 01*
Bore/stroke	*mm X mm*	75 X 90.5
Connecting rod assembly		*Connecting rod with scored big end, tightened piston axis* *High characteristic steel*
Oil pump		*Variable displacement* *driven by the command-control*
Cylinder head		*A57 Aluminium with copper added with heat treatment* *Gravity casting* *Exhaust intake integrated into the cylinder head casting*
Turbocharging		*New generation turbocharger, optimised output, integrated dump valve, electric wastegate*
Engine block		*Vacuum-cast pressurised aluminium with inserted hybrid cast cylinder liners*
Oil pump		*Variable displacement driven by the command control*
Injection		*Central direct injection, 5-hole injectors with laser drilling technology* *High pressure petrol pump, 250 bars*
Distribution		*2 composite tubular camshafts* *wet belt drive, DLC on cams*
Valve drive command		*Front feed by mechanical lifters*
Valves per cylinder		*4 valves per cylinder*
Engine length	*mm*	*604.5*
Engine height	*mm*	*683.5*
Engine width	*mm*	*586*
Mass according to PSA standard	*kg*	*84 kg*
Fuel	*RON*	*91-98*
Cooling		*Thermo-management controlled by thermostat*
Exhaust line		*Emission control elements integrated as a single piece under turbocharger with:* *Catalytic converter + GPF*

The exhaust line was instrumented as shown in the figure below:

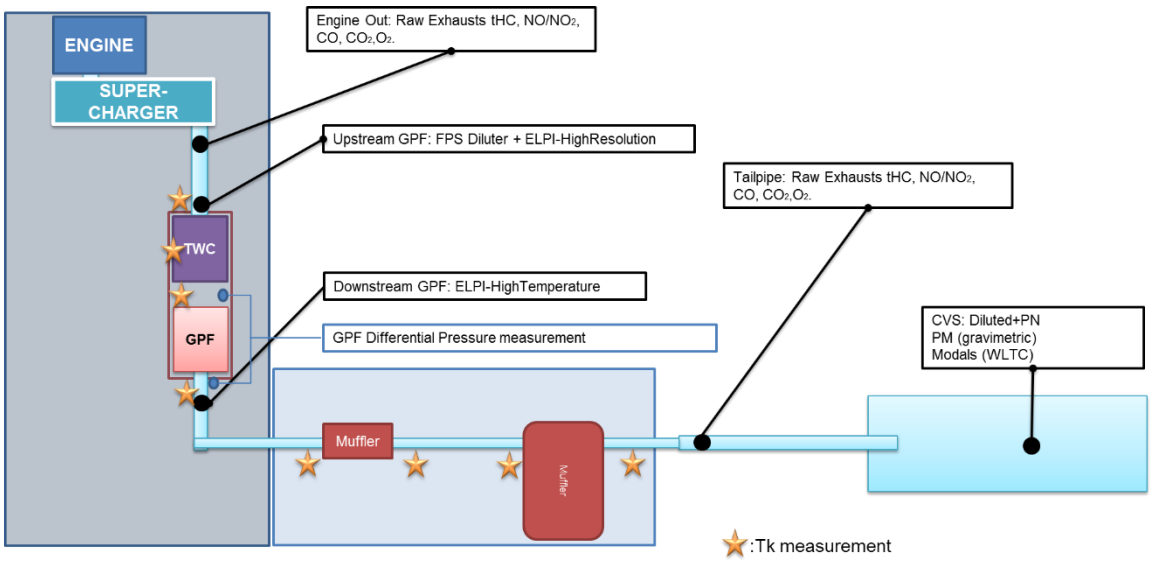


Figure 3.3 Exhaust line instrumentation (Tk measurement means exhaust temperature measurement)

3.4. PN MEASUREMENT USING ELPI

To perform simultaneously upstream and downstream of the aftertreatment system TWC/GPF (i.e. engine-out and tailpipe) particulates emissions measurements in the range of 7 nm to 1 µm, 2 Dekati® ELPI+ were used. The upstream instrument was used in High Resolution mode downstream of a Fine Particle Sampler that allows a x10 dilution ratio with its constant monitoring and recording. Hot dilution allowed to lower dew point of sampled aerosol and prevented condensates. The downstream instrument was used in High Temperature mode at 180°C without dilution in a 300°C heated line. This setup avoids water condensation without requiring any dilution, thus ensuring ideal concentration ranges downstream of the GPF.

3.5. OBD RECORDS AND INJECTORS DRIFT CHECK

All available on-board diagnostic (OBD) data were recorded using during the vehicle tests.

Additionally, measurements of injection timing and duration were performed using a current clamp and AVL Xion™ fast acquisition platform. The data was processed using AVL INDIcom software to compute injection timings during a 15' stabilized engine driving at 100kph between WLTC cold and WLTC hot cycles. This procedure allowed to monitor any possible injector drift, for example loss of permeability due to injector fouling.

3.6. EXPERIMENT DESIGN: PRECONDITIONING, WLTC COLD, WLTC HOT AND RDE CYCLE

Each fuel was tested using the following procedure:

- Purge of the previous fuel and drive 15-20 km on open road to allow the ECU to adapt to the new fuel.

- Preconditioning of the vehicle using WLTC cycle – road law adjustment if needed

- Soaking
- WLTC cold cycle
- Constant speed at 100 km/h during 15' (injectors drift check)
- WLTC hot cycle
- Soaking
- RDE cycle

Road law parameters were obtained using coast down procedure of the WLTP methodology. Here are the resulting coefficients:

Table 3.2 Road law used for the test campaign

Road Load		
Coeff A:	119.00	N
Coeff B:	1.5444	N/kph
Coeff C:	0.03040	N/kph²
Inertia:	1500	kg

3.6.1. WLTC

The WLTC follows the driving profile shown in the figure below, having the characteristics summarized in the table below.

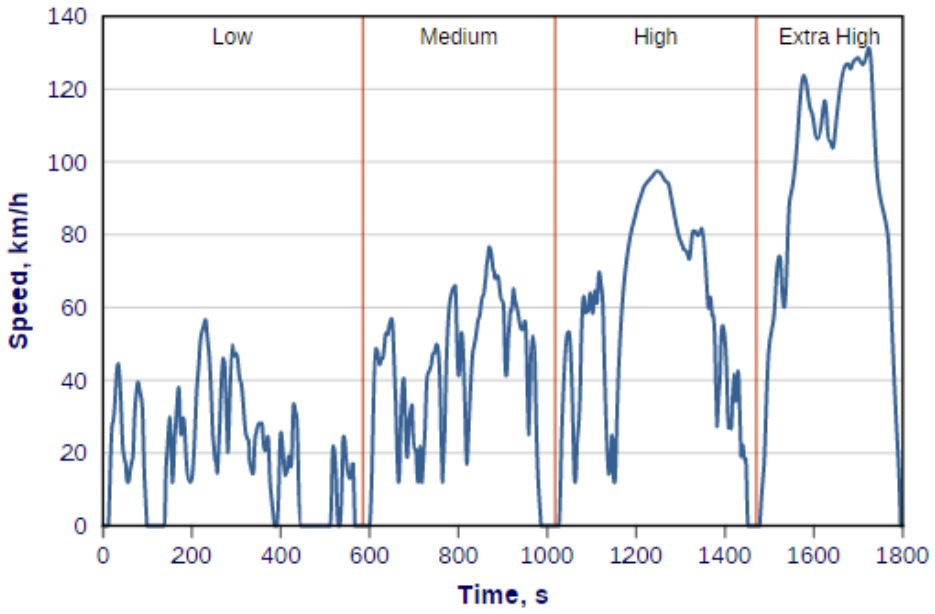


Figure 3.4 WLTC cycle for class 3b vehicles (from dieselnet.com)

Table 3.3 Characteristics of class 3b WLTC cycle (from dieselnet.com)

Phase	Duration	Stop Duration	Distance	p_stop	v_max	v_ave w/o stops	v_ave w/ stops	a_min	a_max
	s	*s*	*m*		*km/h*	*km/h*	*km/h*	*m/s²*	*m/s²*
Class 3b (v_max ≥ 120 km/h)									
Low 3	589	156	3095	26.5%	56.5	25.7	18.9	-1.47	1.47
Medium 3-2	433	48	4756	11.1%	76.6	44.5	39.5	-1.49	1.57
High 3-2	455	31	7162	6.8%	97.4	60.8	56.7	-1.49	1.58
Extra-High 3	323	7	8254	2.2%	131.3	94.0	92.0	-1.21	1.03
Total	**1800**	**242**	**23266**						

A reminder of the emissions limits according to the Euro standards is provided in the table below:

Table 3.4 EU emission standards for passenger cars (category M1) (from dieselnet.com)

Stage	Date	CO	HC	HC+NOx	NOx	PM	PN
		g/km					*#/km*
Positive Ignition (Gasoline)							
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	-	-
Euro 2	1996.01	2.2	-	0.5	-	-	-
Euro 3	2000.01	2.30	0.20	-	0.15	-	-
Euro 4	2005.01	1.0	0.10	-	0.08	-	-
Euro 5	2009.09[b]	1.0	0.10[d]	-	0.06	0.005[e,f]	-
Euro 6	2014.09	1.0	0.10[d]	-	0.06	0.005[e,f]	6.0×10^{11} [e,g]

* At the Euro 1..4 stages, passenger vehicles > 2,500 kg were type approved as Category N_1 vehicles
† Values in brackets are conformity of production (COP) limits
a. until 1999.09.30 (after that date DI engines must meet the IDI limits)
b. 2011.01 for all models
c. 2013.01 for all models
d. and NMHC = 0.068 g/km
e. applicable only to vehicles using DI engines
f. 0.0045 g/km using the PMP measurement procedure
g. 6.0×10^{12} 1/km within first three years from Euro 6 effective dates

3.6.2. RDE cycle

The RDE cycle is extracted from on-road RDE measurement campaigns in the area of Rouen, France. Its speed profile, illustrated in the figure below, complies with the RDE requirements.

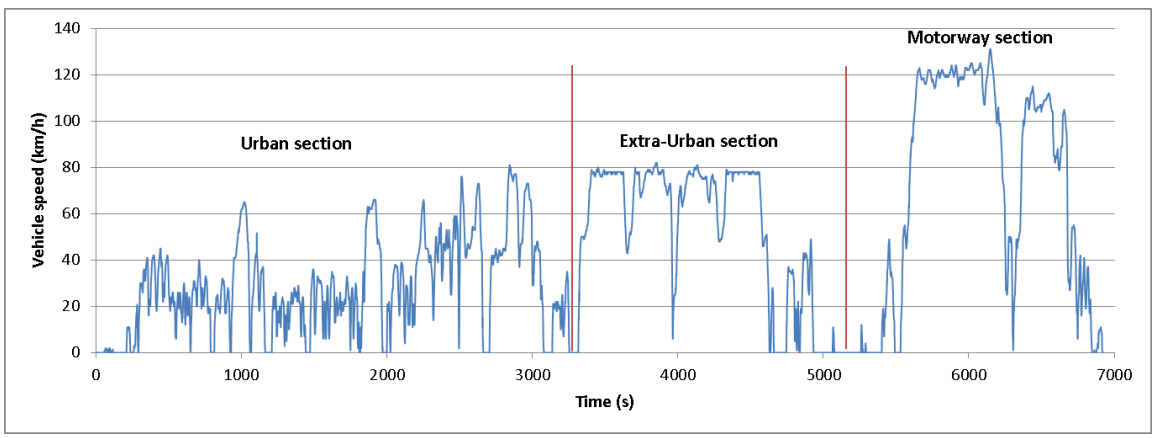


Figure 3.5 Speed profile of the RDE cycle used in the test campaign.

Table 3.5 RDE cycle main characteristics – Total distance: 86.7 km; total duration: 6922 s.

Routes	Average speed (km/h)	Distance (km)	Distance shares
Urban	29.4	30.0	35%
Extra-urban	74.3	29.2	34%
Motorway	113.6	27.5	32%

3.7. DATA POST-TREATMENT

The rolling test bench acquisitions (regulated pollutants) were post-treated according to HORIBA VETS software.

ELPI+-HR (engine-out) and ELPI+-HT (tailpipe) acquisitions were post-treated using Dekati post-treatment software.

A synthesis file was produced with synchronized datasets (OBD, Exhaust line temperatures, Exhaust Flow rate) for each test.

The following metrics were extracted:

- Engine-out and tailpipe PN emission: concentration, emission factor, mean geometric diameter (MGD), size distribution;
- Computed data: Instantaneous GPF efficiency, frequency analysis to compare fuels with median/modal efficiency and median/modal MGD, % of PN having a diameter smaller than 23nm;
- CO_2 emissions expressed in g/km and g/kWh at the wheel;
- Regulated pollutants emissions in g/s and g/km;
- Fuel consumption expressed in g/kWh at the wheel;
- Time to catalyst light-off (WLTC cold conditions)

3.8. TEST PROGRAMME DESIGN

3.8.1. Test design objectives

The early plan for this test programme was to design a fuel matrix to study the effects of E150, light aromatics (<C9) and heavy aromatics (≥C9) on PN upstream (engine-out) and downstream (tailpipe) of the GPF. However, it was not possible to blend fuels that contained a high (~25%v/v) proportion of heavy aromatics that simultaneously had a high E150 and so the desired fuel matrix could not be accomplished. This led to a change in the primary objective to focus on the effects of total aromatics and E150. Light aromatics (<C9) and heavy aromatics (≥C9) were still factored into the blending of the fuels and the study of their effects became a secondary objective of the study.

A third objective was added by including a vector of higher oxygenate fuels on one arm only of the fuel matrix to look at the effects of high oxygenates on PN emissions.

In addition to the fuel properties in the designed matrix, there was also interest in whether the following properties showed any correlation with PN emissions:

- The three PM indices widely referenced in the literature: E150 PM index, E130-E170 PM index and the Honda PM Index.

- Additional fuel properties: T90, FBP, IBP, T10, DVPE, Yield Sooting Index (YSI) and Adiabatic Flame Temperature (AFT)

All these indices and additional properties are correlated to a greater or lesser extent with the design fuel properties of E150, aromatics and oxygenates and hence their effect cannot be evaluated independently from these. However, a simple correlation with PN emissions can be investigated.

3.8.2. Fuel Matrix

The primary design of this programme was a matrix varying E150 (3 levels) and total aromatics (2 levels). These are fuels 2,3,5,6,7 & 10 in ***Figure 3.6*** below. The 6 fuels in this primary matrix all have a greater proportion of light aromatics (<C9) than heavy aromatics (≥C9) and they all have ~10%v/v oxygenates. An additional vector of high 26% oxygenate fuels at 20% aromatics (also with a greater proportion of lighter <C9 aromatics) seeks to determine whether the effect of E150 is different at higher oxygenates. These are fuels 11,12 & 13.

		Oxygenates			
		~26% v/v	~10%v/v		~10%v/v
E150	~92%	Fuel 13	Fuel 10		Fuel 7
	~85%	Fuel 12	Fuel 6		Fuel 5
	~80%	Fuel 11	Fuel 2		Fuel 3
		~20%v/v	~20%v/v		>34%v/v
		Aromatics			

Figure 3.6 Fuel matrix of primary fuel properties

A secondary objective was to evaluate the impact of light (<C9) aromatics and heavy (≥C9) aromatics which, despite the difficulties in blending, were still reasonably well de-correlated in the final fuel matrix. Fuels 1 & 4, which have a greater proportion of heavy (≥C9) aromatics, were added to the matrix. They contain 10% oxygenates and are only present at low E150 as it was not possible to blend high aromatic fuels (>35%v/v) with a high proportion of ≥C9 aromatics that also had high E150.

Finally, two additional fuels were added to the matrix: Fuel 8 is an equal blend of <C9 and ≥C9 aromatics and Fuel 9 is a reference fuel at a mid-aromatics level of 27%v/v. Fuel 9, being a somewhat central point in the matrix, was used by the test facility as a reference fuel and received additional repeats throughout the programme.

		Oxygenates			
		~26% v/v	~10%v/v	~10%v/v	~10%v/v
E150	~92%	Fuel 13	Fuel 8	Fuel 9	Fuel 7
			Fuel 10		
	~85%	Fuel 12	Fuel 6		Fuel 5
	~80%	Fuel 11	Fuel 2		Fuel 1
			Fuel 4		Fuel 3
		~20%v/v	~20%v/v	27%v/v	>34%v/v
		Aromatics			

Figure 3.7 Complete Fuel Matrix

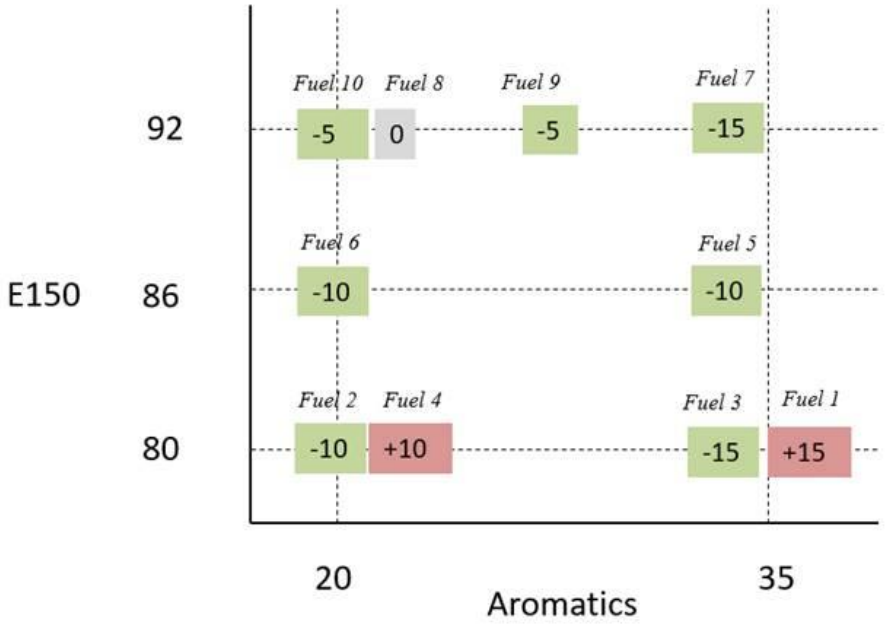


Figure 3.8 Fuel matrix seen in the E150-Aromatics plan. The numbers in the boxes represent (> C9 aromatics - < C9 aromatics)

Colour code: green box = more light aromatics, red box = more heavy aromatics, grey box = 50/50

The following table gathers the tested fuels characteristics, and the graph below shows the distillation curves:

Table 3.6 Tested gasoline physical-chemical properties

Test	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8	Fuel 9	Fuel 10	Fuel 11	Fuel 12	Fuel 13
RON	96,9	96	96,5	TBA	97,3	97,5	96,3	96	97,6	95,8	96,8	98,7	98,3
MON	85,9	86,2	85,5	TBA	86	86,8	85,4	87	86,6	86,2	86,3	86,9	87,2
Density at 15°C [kg/m³]	0,7548	0,748	0,7617	0,7343	0,7649	0,744	0,7553	0,729	0,7416	0,733	0,7583	0,7552	0,7438
DVPE at 37°C [kPa]	63	63,3	70	59,2	60,8	61,3	62,4	58,7	64,3	65,6	58,1	52,4	62,1
Sulphur [mg/kg]	1,5	3,5	1,6	2,7	1,4	1,9	1,5	1,8	2,3	1,7	1,6	2,2	1,7
PIONA													
Paraffines [%vol]	7	6,8	6,8	4,3	6,2	5,4	7,7	5,9	5,1	7,1	7,4	5,8	6,6
Isoparaffins [%vol]	33,3	36,6	28,8	47,6	27,8	38,7	31,3	48,8	38,9	42,8	27,7	28,5	31,9
Olefins [%vol]	9,3	11	9,8	9,9	10,7	10,4	10,4	9,3	9,6	10,2	10,1	10,3	9,6
Naphthenes [%vol]	6,2	11,9	5,8	6,1	4,4	12,1	6	5,4	9	7,7	3,6	5,7	4,7
Aromatics [%vol]	34,1	20,9	35	20,6	39,3	21	34,6	20	27,2	20,9	20,7	20,7	20,9
Unknowns	0,2	2,9	3,5	1,5	1,6	2,3	0,4	0,7	0,1	1,2	4	2,5	0,7
Benzene [%vol]	0,09	0,02	0,06	0,12	0,08	0,05	0,08	0,08	<0,1	0,08	0,03	0,06	0,08
<C9 aromatics [%vol]	9,8	14,9	25,1	5,3	24,8	15,6	24,8	10,4	16,4	15	15,3	15,4	15,1
≥C9 aromatics [%vol]	24,3	6	9,9	15,3	14,5	5,4	9,8	9,6	10,8	5,9	5,4	5,3	5,8
Oxygenates													
Ethanol [%vol]	5	4,9	5,3	5,1	5,1	5,2	5	5	5,2	5,1	15,3	15,4	14,8
MTBE [%vol]	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1
ETBE [%vol]	4,9	5	5,1	4,8	4,9	4,9	4,8	4,8	4,9	5	11,2	11,1	10,9
Other [%vol]	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1
Oxygenates - Total [%wt]	9,9	9,9	10,4	10,1	10,1	10,2	9,8	9,8	10,1	10,3	26,5	26,6	25,6
Oxidation Stability [min]	>360	>360	>360	>360	>360	>360	>360	>360	>360	>360	>360	>360	>360
Copper Corrosion (3h at 50°C)	1A	1A	1A	1A	1A	1A	1A	1A	1A	1A	1A	1A	1A
Existent Gum - Unwashed [mg/100ml]	<1	<1	<1	<1	<1	<1	<1	<1	<1	1	<1	<1	<1
Existent Gum - Washed [mg/100ml]	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Lead [mg/l]	<2,5	<2,5	<2,5	<2,5	<2,5	<2,5	<2,5	<2,5	<2,5	<2,5	<2,5	<2,5	<2,5
Carbon [%wt]	84,22	83,82	84,43	83,23	84,71	83,53	84,46	83,23	83,84	83,4	79,45	79,15	79,25
Hydrogen [%wt]	13,19	13,58	12,89	14,08	12,68	13,77	12,97	14,1	13,47	13,9	13,26	13,48	13,56
Oxygen [%wt]	2,59	2,59	2,68	2,69	2,61	2,7	2,56	2,68	2,69	2,7	7,29	7,36	7,19
Gross Calorific Value [MJ/kg]	44,72	45,17	44,68	TBA	44,35	44,58	44,75	45,09	44,65	45,2	42,96	42,79	43,11
Gross Calorific Value [MJ/kg]	44,31	44,88	44,03	45,08	44,24	44,87	44,21	45,11	44,57	44,95	42,51	42,53	42,71
Net Calorific Value [MJ/kg]	41,92	42,29	41,95	TBA	41,66	41,68	41,46	42,1	41,79	42,25	40,15	39,7	39,83
Net Calorific Value [MJ/kg]	41,51	41,99	41,23	42,09	41,25	41,95	41,45	42,13	41,71	42	39,69	39,95	40,14

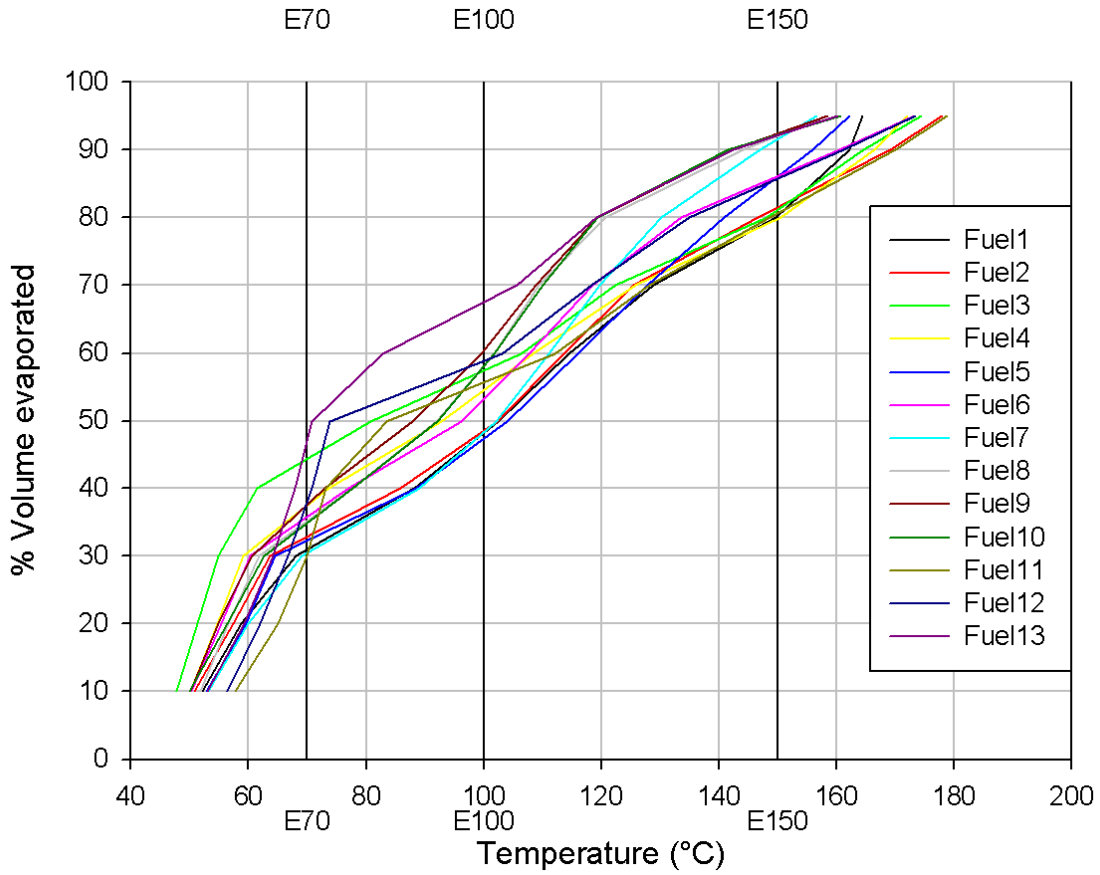


Figure 3.9 Distillation curves of the tested fuels

Table 3.7 Fuels PM indices calculated from the physical-chemical properties of the fuels as referenced in the literature

Fuel	Honda_PM_Index	E130_E170_PM_Index	E150_PM_Index	Yield Sooting Index
Fuel 1	1.59	1.28	1.79	106.8
Fuel 2	0.92	1.69	1.72	80.5
Fuel 3	1.23	1.73	1.72	98.7
Fuel 4	1.18	1.55	1.81	83.8
Fuel 5	1.35	1.24	1.36	106.8
Fuel 6	0.84	1.32	1.36	77.4
Fuel 7	1.15	0.93	0.92	98.2
Fuel 8	0.89	0.78	0.92	77.6
Fuel 9	1.01	0.76	0.94	85.7
Fuel 10	0.8	0.82	0.89	76.0
Fuel 11	0.91	1.8	1.76	67.8
Fuel 12	0.81	1.34	1.37	66.0
Fuel 13	0.78	0.84	0.89	65.2

3.8.3. Correlations between the design fuel properties

E150 was successfully de-correlated from both total aromatics and oxygenates but, since the effect of oxygenates was only studied at low aromatics levels on one axis of the fuel matrix, it was inevitable that there would be some degree of correlation between these two properties.

Table 3.8 Correlation coefficients between the primary design fuel properties

E150			
Aromatics	-0.10		
Oxygenates	-0.01	-0.40	
	E150	**Aromatics**	**Oxygenates**

Total aromatics is the sum of (<C9) aromatics and (≥C9) aromatics and hence these properties cannot all be studied simultaneously. Fuels 1 & 4 are high in ≥C9 aromatics and could only be blended at low E150 and hence some degree of correlation between ≥C9 aromatics and E150 was inevitable. Remarkably, <C9 and ≥C9 aromatics were not in themselves highly correlated, and their effects can be independently evaluated with some degree of robustness.

The high oxygenate fuels were all blended at mid-level <C9 aromatics and hence there is no correlation between oxygenates and <C9 aromatics. However, they all had low levels of ≥C9 aromatics which introduces some correlation between oxygenates and ≥C9 aromatics.

Table 3.9 Correlation coefficients between the secondary design fuel properties

E150				
<C9 Aromatics	0.20			
>=C9 Aromatics	-0.35	-0.22		
Oxygenates	-0.01	-0.06	-0.45	
	E150	**<C9 Aromatics**	**>=C9 Aromatics**	**Oxygenates**

3.8.4. Test Sequence

The test sequence followed a similar principle to another Concawe study (Report 2/19 "Effect of Diesel Fuel Properties on Fuel Economy and Emissions of Three Passenger Cars"). Each of the fuels was tested three times to give a robust estimate of the fuel mean and to make it easier to identify unusual or outlier measurements. The tests were arranged in three blocks with each fuel being tested once per block except for the designated reference Fuel 9 which was generally tested twice in each block for the purpose of regular cross-checking of the vehicle.

Tests were carried out on three cycles: WLTC Cold, WLTC Hot and RDE. Data for the individual phases of the two WLTC cycles were extracted from the data files.

Ideally the sequence within each block would be randomised, but this approach was modified a little so that the average position of the repeats on each fuel was close to the midpoint of the overall sequence. Such an arrangement ensures that, if linear drift is present in the results and are adjusted for it, the fuel means are minimally affected. In practice the three blocks were run as a continuous sequence with no

gap between them although the third block was interrupted for several weeks due to a nationally imposed lockdown during the coronavirus pandemic. Inevitably there were some failed tests and operational issues which led to the original sequence undergoing some slight modifications which are detailed in the section of data quality. The designed test sequence is shown below.

Table 3.10 Test sequence

BLOCK 1		BLOCK 2		BLOCK 3	
Design Test order	**Fuel**	**Design Test order**	**Fuel**	**Design Test order**	**Fuel**
1	Fuel 9	15	Fuel 10	29	Fuel 3
2	Fuel 11	16	Fuel 2	30	Fuel 4
3	Fuel 12	17	Fuel 9	31	Fuel 5
4	Fuel 6	18	Fuel 8	32	Fuel 8
5	Fuel 7	19	Fuel 1	33	Fuel 11
6	Fuel 3	20	Fuel 4	34	Fuel 9
7	Fuel 10	21	Fuel 13	35	Fuel 13
8	Fuel 1	22	Fuel 12	36	Fuel 7
9	Fuel 9	23	Fuel 7	37	Fuel 2
10	Fuel 5	24	Fuel 6	38	Fuel 6
11	Fuel 13	25	Fuel 5	39	Fuel 1
12	Fuel 2	26	Fuel 9	40	Fuel 12
13	Fuel 4	27	Fuel 3	41	Fuel 10
14	Fuel 8	28	Fuel 11	42	Fuel 9

4. PHASE 1 - EXPERIMENTAL RESULTS

4.1. CO_2 EMISSIONS

In the graphs below, CO_2 emissions are expressed in g/km, the bar showing the average value over the 3 repeats of each fuel, and the error bar showing the standard error of the mean (SEM, approximately 1 g/km) of the experimental matrix. The red dots show the calculated "theorical CO_2 emissions", assuming that all fuels would provide the same engine efficiency (Fuel 9 was taken as a reference), and thus their CO_2 emissions would only depend on their emission factor (CO_2 intensity expressed in MJ/km). This was used as a way to monitor the consistency of the experimental results and quickly spot any potential outlier.

The formula used to compute "theorical CO_2 emissions" is:

$$CO2theorical\ (\frac{g}{km}) = \overline{CO2\_RefFuel} \times {}^{CO2\ Intensity\ Candidate\ Fuel}/_{CO2\ Intensity\ Reference\ Fuel}$$

Where CO_2 Intensity is computed according to the mass percentage of Carbon in the fuel (%m C), the molar mass of C and CO_2, and Net Calorific Value in MJ/kg:

$$CO2\ Intensity = \frac{\%m\ C\ \times\ {}^{MM\_CO2}/_{MM\_C}}{Net\ Calorific\ Value * 1000}$$

The results are shown in the three graphs below, respectively on the cold WLTC, on the hot WLTC and on the RDE cycle. The extent of variation between the most extreme fuels is up to 8 g/km (or 5.5% of the CO_2 emissions). The measured values are quite consistent with the "theorical CO_2 emissions", although the calculated values would predict a smaller range of variation. This consistency means that all fuels provide a similar engine efficiency. Consequently, CO_2 emissions mostly depend on the fuel's emissions factor, and fuel consumption (not shown here) only depends on the fuel's energy density (expressed in MJ/L).

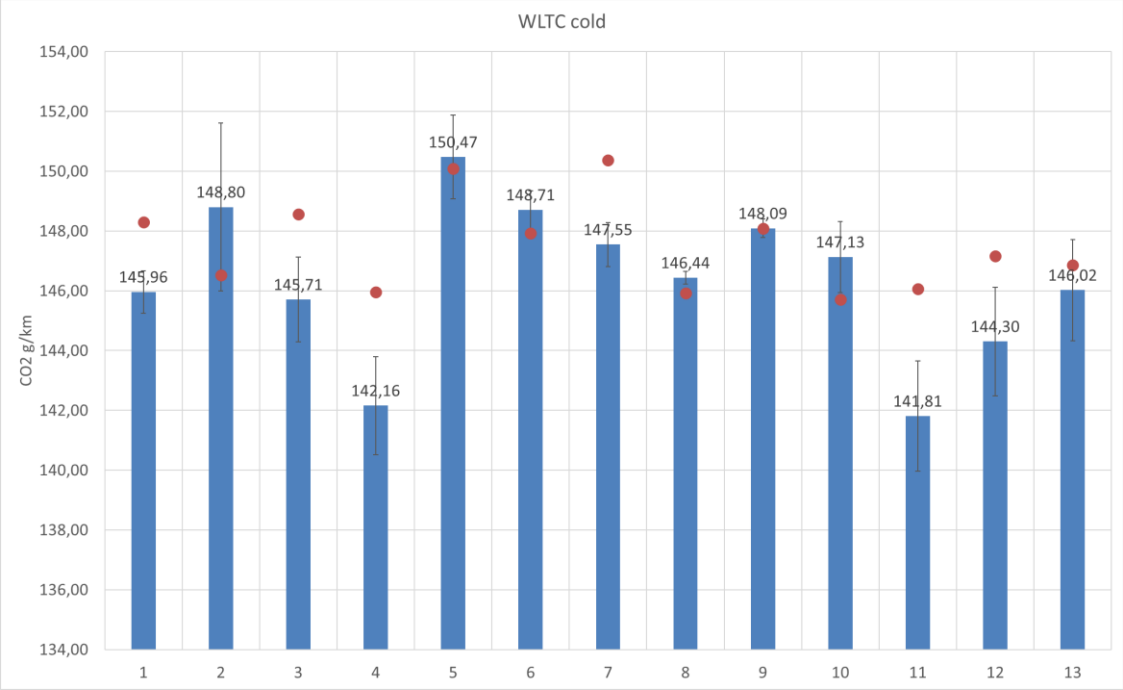


Figure 4.1 Cold WLTC CO_2 emission, red dots represent theoretical CO2 emissions

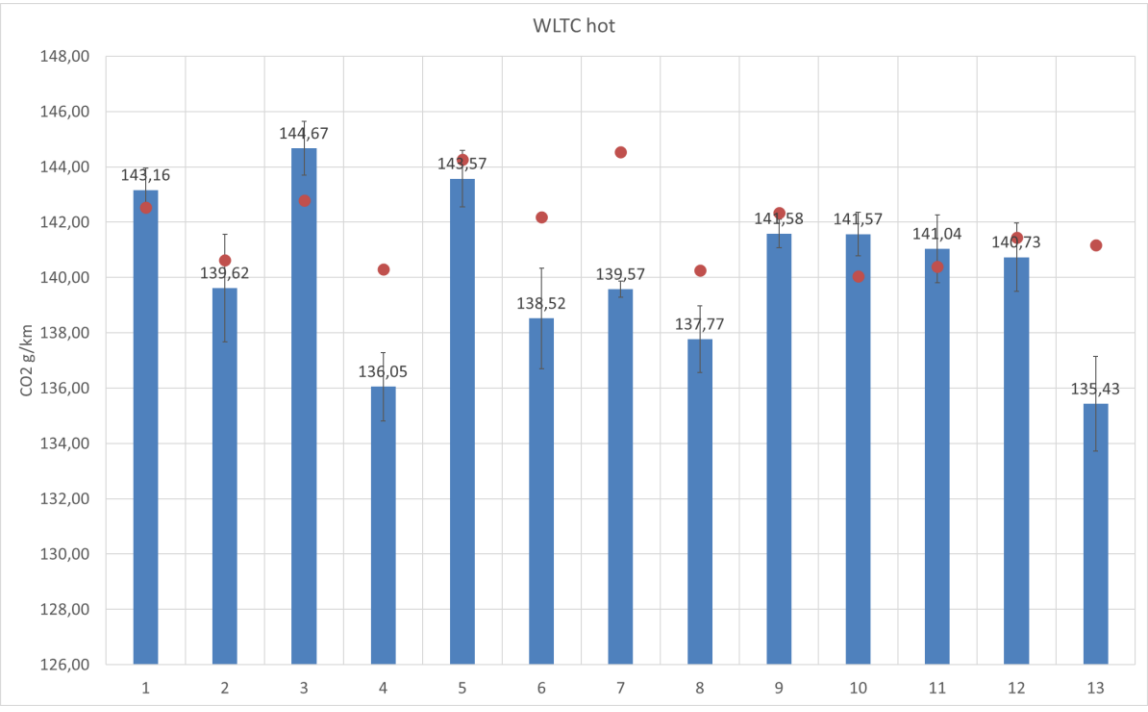


Figure 4.2 Hot WLTC CO_2 emission, red dots represent theoretical CO2 emissions

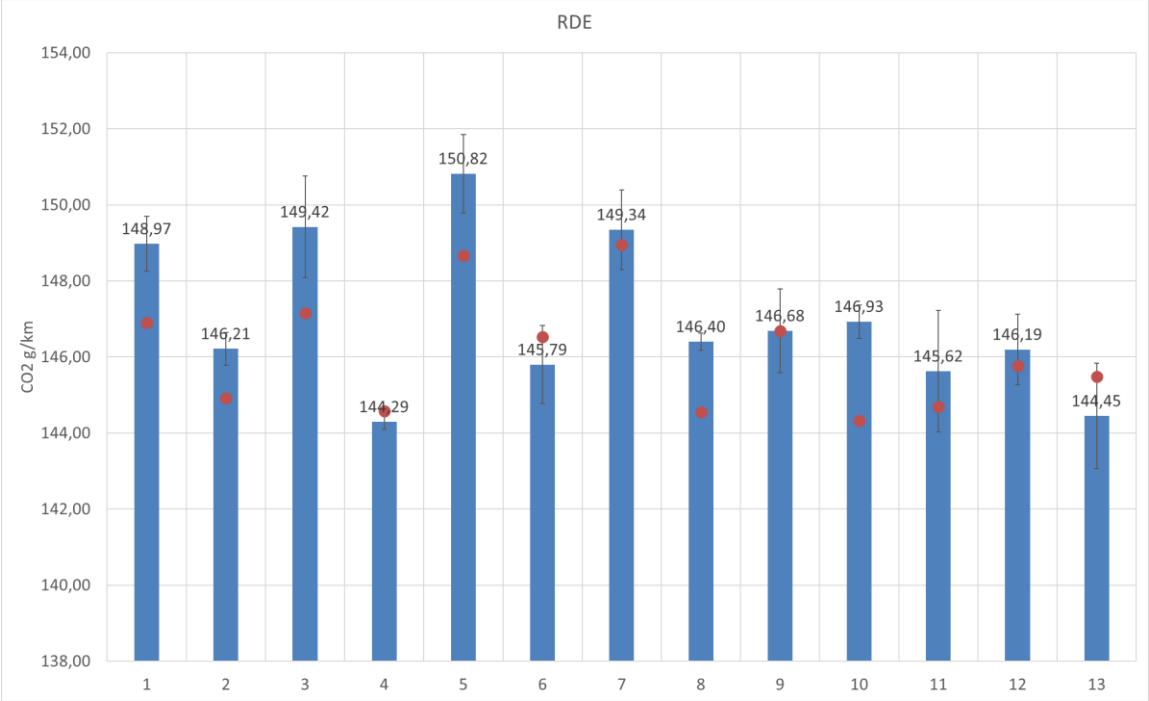


Figure 4.3 Cold RDE CO_2 emission, red dots represent theoretical CO2 emissions

4.2. PN EMISSIONS

4.2.1. Tailpipe particulates having a diameter bigger than 23 nm

As mentioned above, the tailpipe particulates number emissions with a diameter bigger than 23 nm (TP PN 23) were measured using two different devices: an ELPI and a SPCS (official measurement). The results are shown in the four graphs below for the cold WLTC, the hot WLTC and the RDE cycle.

First, it can be observed that the two measurement devices, although being totally independent and using different measurement techniques, show results consistent with each other. Furthermore, the repeatability of the test is fairly good for this kind of complex measurement, which allows to distinguish the emissions of some fuels (not all of them) from the measurement noise.

Second, all the average PN emissions measurements are below the Euro 6d standard limits, although some individual measurements (e.g. Fuel 3 on the cold WLTC) may have been measured beyond the limit. The most challenging conditions to comply with the emissions limits are the shorter cycles including a cold start (e.g. cold WLTC), because most of the particulates are emitted during the first minutes after cold start, as will be shown later in this report.

Last, the extent of variation between the lowest and the highest emitters is between 3- and 5-fold, with fuels 8, 9, 10 and 13 being consistently among the low emitters while fuels 1, 3, 5 and 11 are consistently among the high emitters.

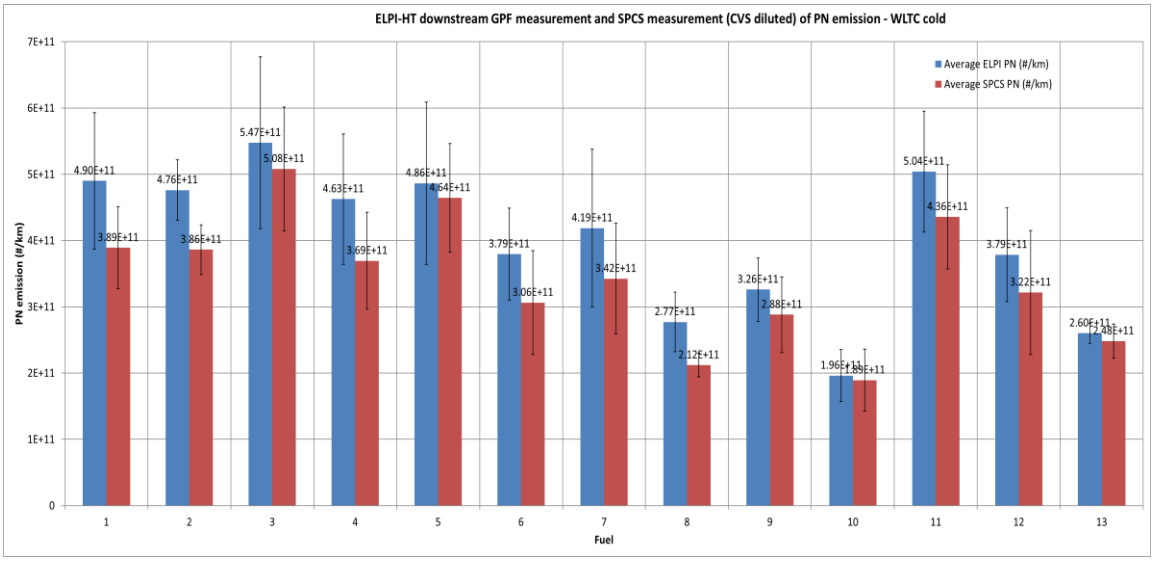


Figure 4.4 TP PN 23 emissions measured with the ELPI (blue) or with the SPCS device – WLTC cold

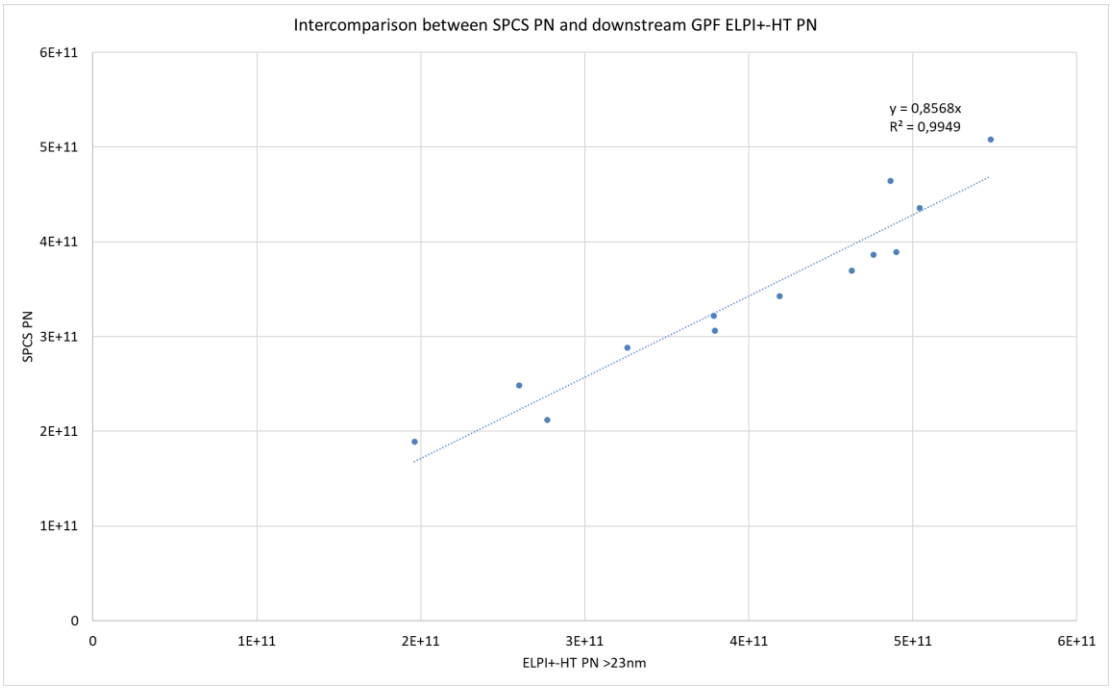


Figure 4.5 Parity plot between TP PN 23 emissions measured with the ELPI (blue) and with the SPCS device – WLTC cold

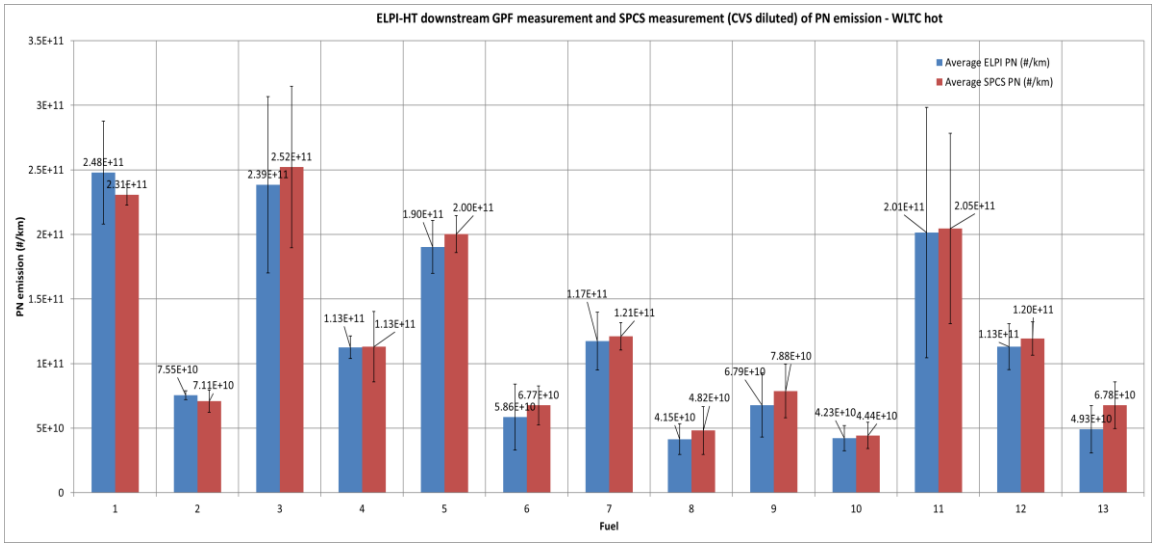


Figure 4.6 TP PN 23 emissions measured with the ELPI (blue) or with the SPCS (red) device – WLTC hot

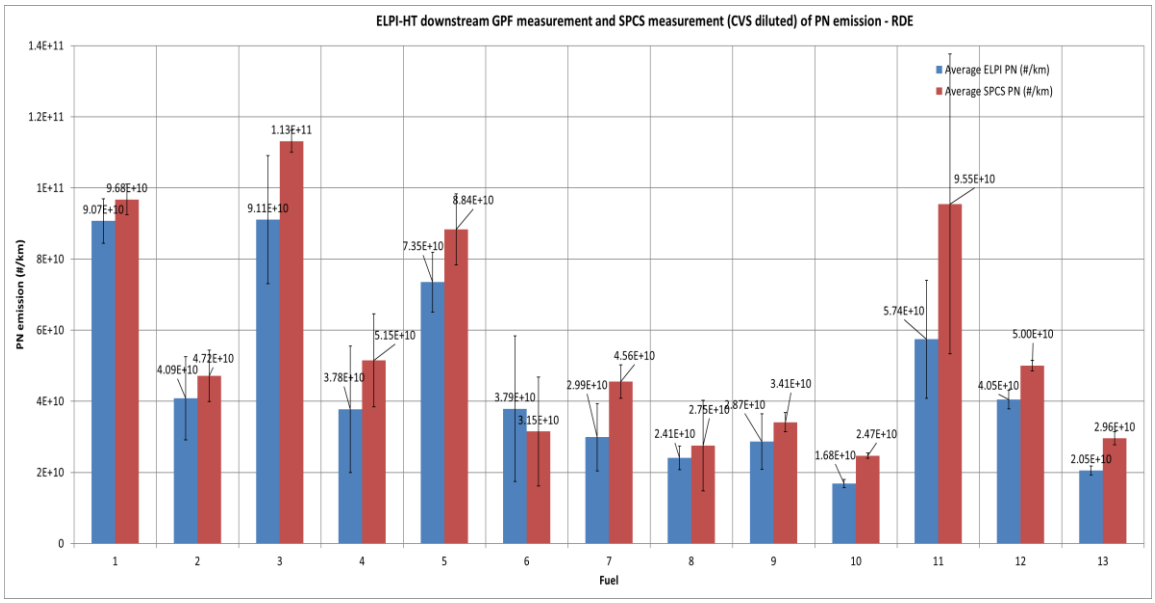


Figure 4.7 TP PN 23 emissions measured with the ELPI (blue) or with the SPCS device – RDE cycle

4.2.2. Tailpipe particulates having a diameter smaller than 23 nm

The measurement performed with the ELPI device allows to calculate the share of TP PN emissions having a diameter smaller than 23 nm. ELPI method is measuring particle size distribution thereby allowing to calculate PN emissions above 23nm and smaller than 23nm. This share ranges between 25% and 50% depending on the fuels and on the driving conditions. Consequently, if the proposal of measuring the PN emissions down to 10 nm is retained for the future emissions standards, this amount would need to be added on top of the TP PN 23 emissions shown above.

4.2.3. GPF filtration efficiency

GPF's filtration efficiency is lower than its Diesel counterpart. As a matter of fact, GPF's filtration efficiency varies a lot during the cycle, due to a continuous process of regeneration of soot cake in the honeycomb structure of the particulate filter. As this soot cake is a major contributor of DPF efficiency (> 99%), its absence or its continuous regeneration during charge lift-off and oxygen supply could explain lower efficiency. The average GPF's filtration efficiency ranges between 70% and 80% on the WLTC (cold and hot) and between 80% and 90% on the RDE cycle that is longer. At this stage, there is no clear evidence of "fuel properties"-related effect on GPF's filtration efficiency.

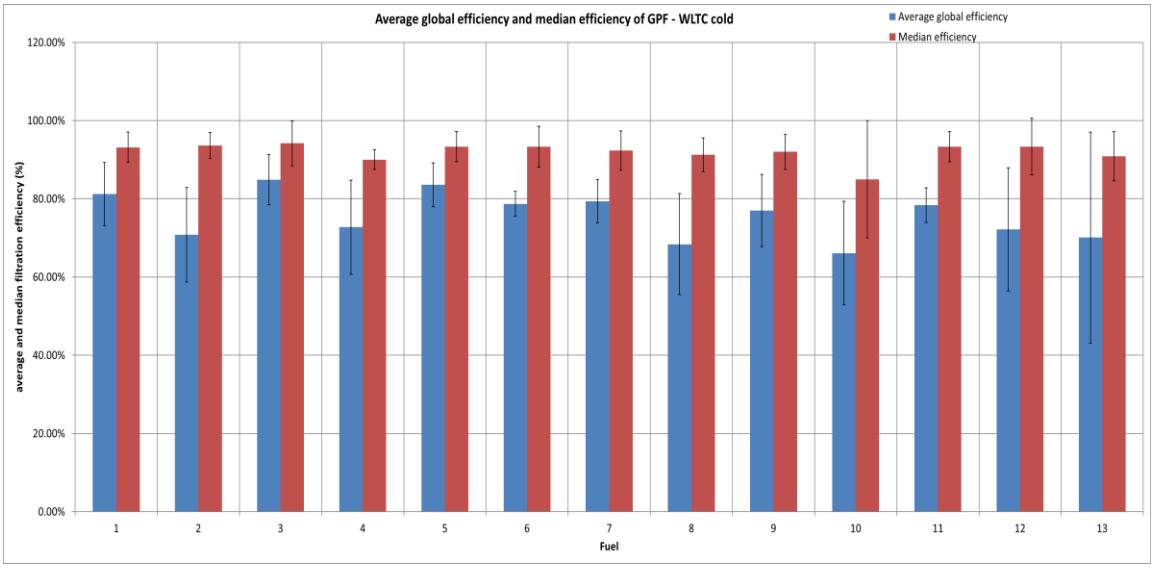


Figure 4.8 Average and median GPF efficiency – WLTC cold

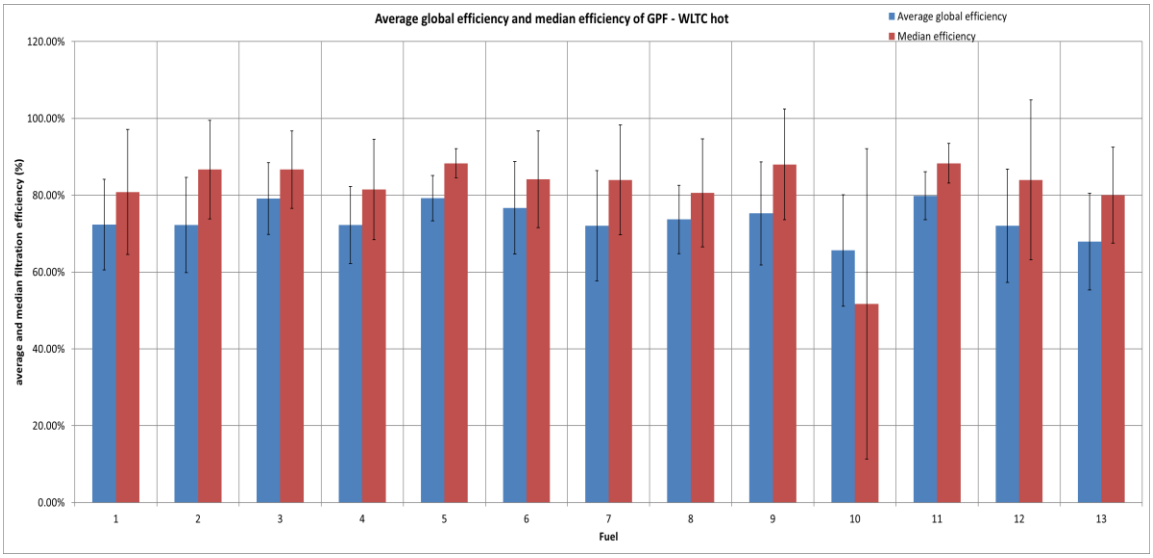


Figure 4.9 Average and median GPF efficiency – WLTC hot

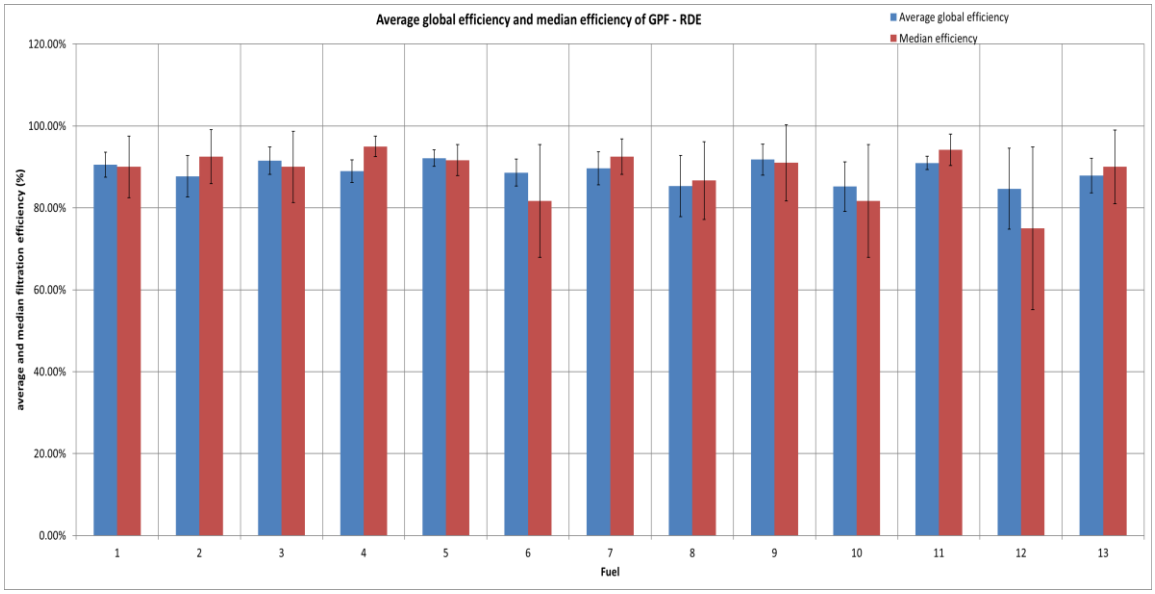


Figure 4.10 Average and median GPF efficiency – RDE

4.2.4. WLTC by-phase PN emission

An analysis of the PN emissions was performed for each 4 phases of the WLTC as can be observed in the two figures below, respectively for the cold WLTC and for the hot WLTC.

In the cold WLTC, it is clear that most of the particulates (between 63% and 84%) are emitted during the first phase of the driving cycle, which includes the cold start. This result agrees with the existing literature, which evaluates cold start as a major contributor of PN emissions.

In the hot WLTC, not only the overall PN emissions are lower, but also the contribution of the first phase is smaller as it is no longer associated with a cold start. It can be observed as an important contribution of the last phase (extra high) to the PN emissions: it is also in agreement with the literature, which evaluates transients and higher loads as significant contributors to the PN emissions.

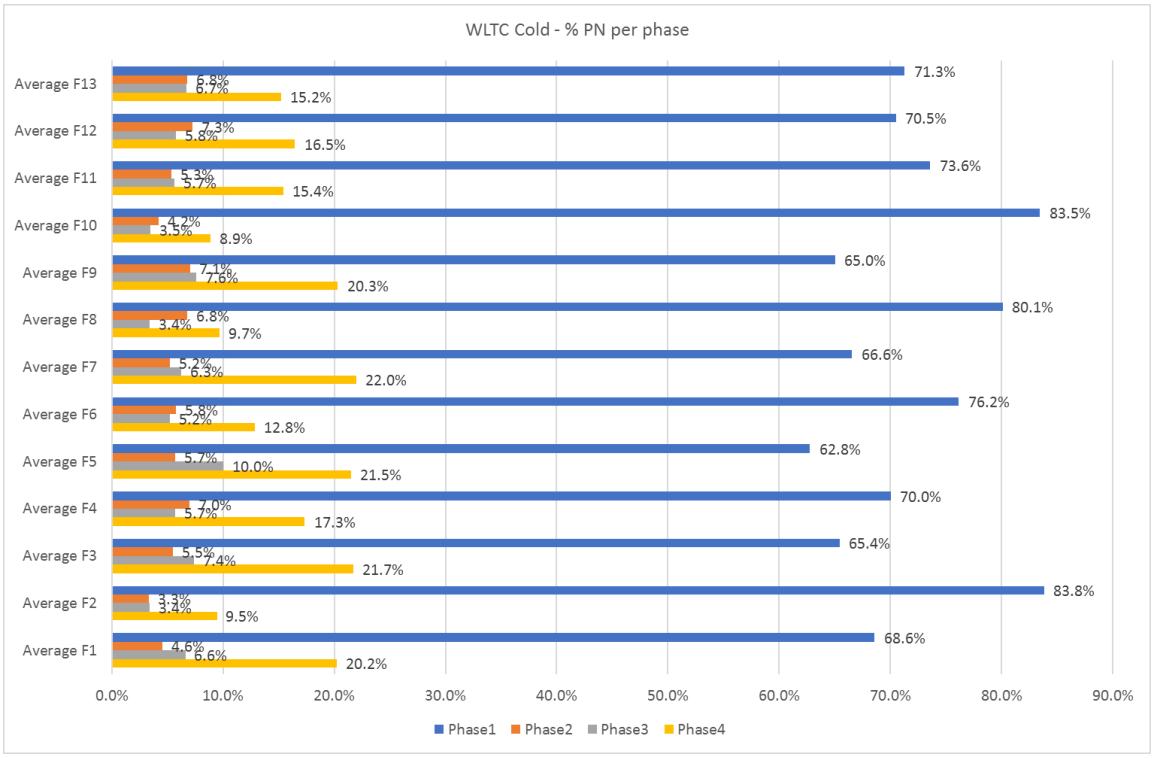


Figure 4.11 Cold WLTC by-phase PN emissions

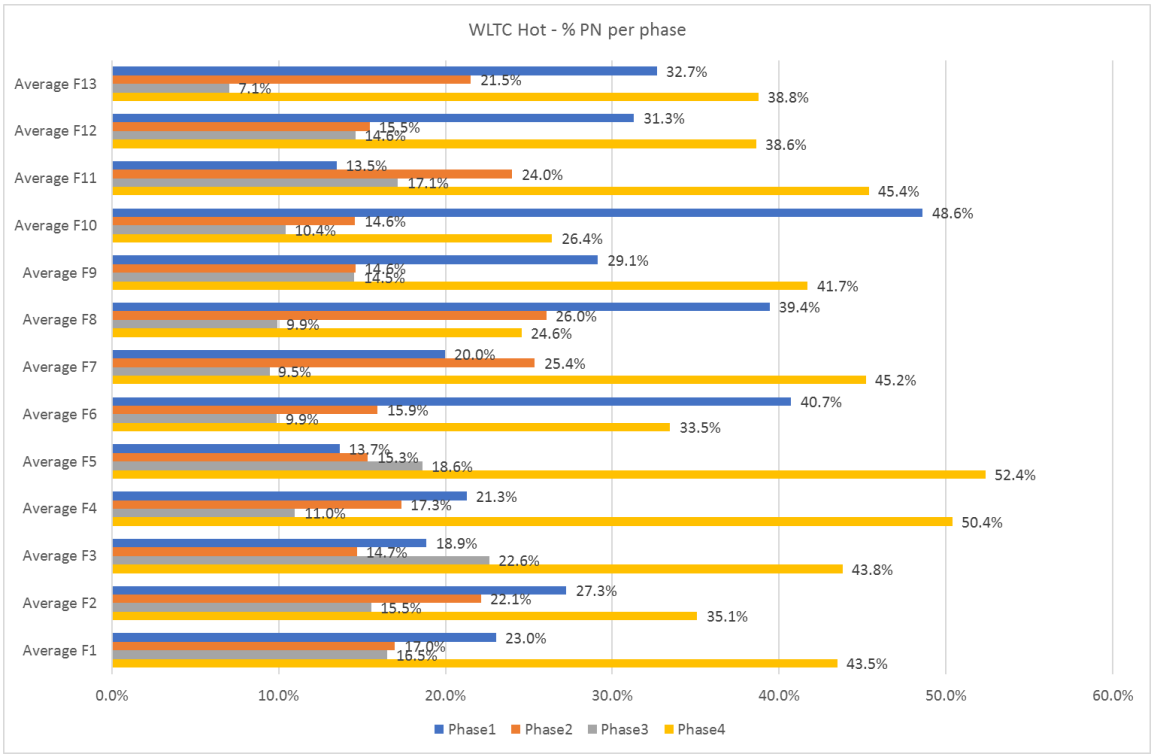


Figure 4.12 Hot WLTC by-phase PN emissions

4.3. ENGINE-OUT GASEOUS EMISSIONS

The three figures below show the engine-out CO, HC and NOx emissions for each of the tested fuels, respectively on the cold WLTC, on the hot WLTC and on the RDE cycle. Constant level of emissions of each of these pollutants can be observed, independent on the tested fuel, whatever the driving cycle.

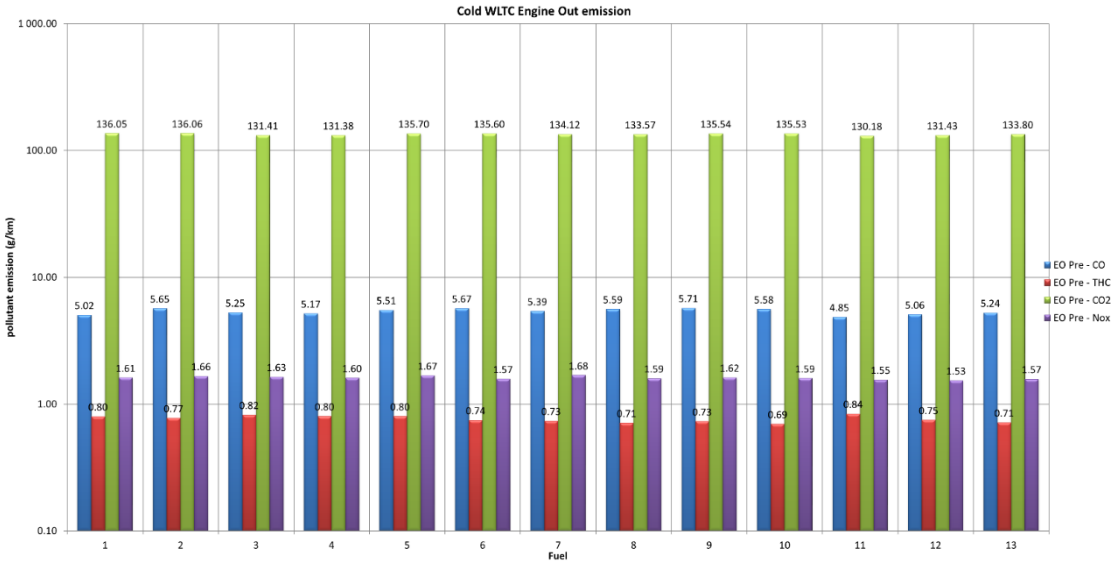


Figure 4.13 Cold WLTC engine-out emissions for each of the test fuels (in g/km)

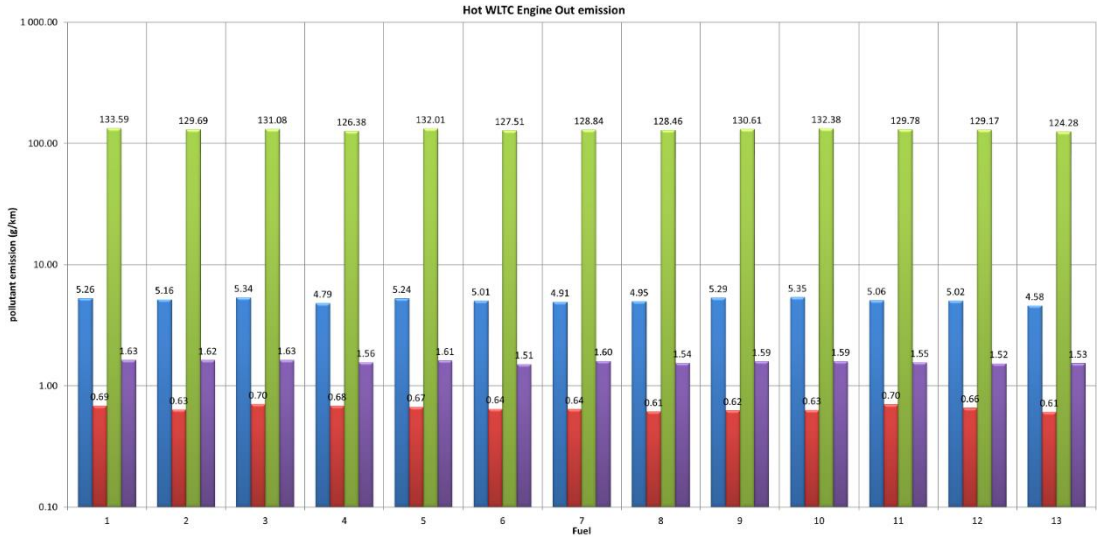


Figure 4.14 Hot WLTC engine-out emissions for each of the test fuels (in g/km)

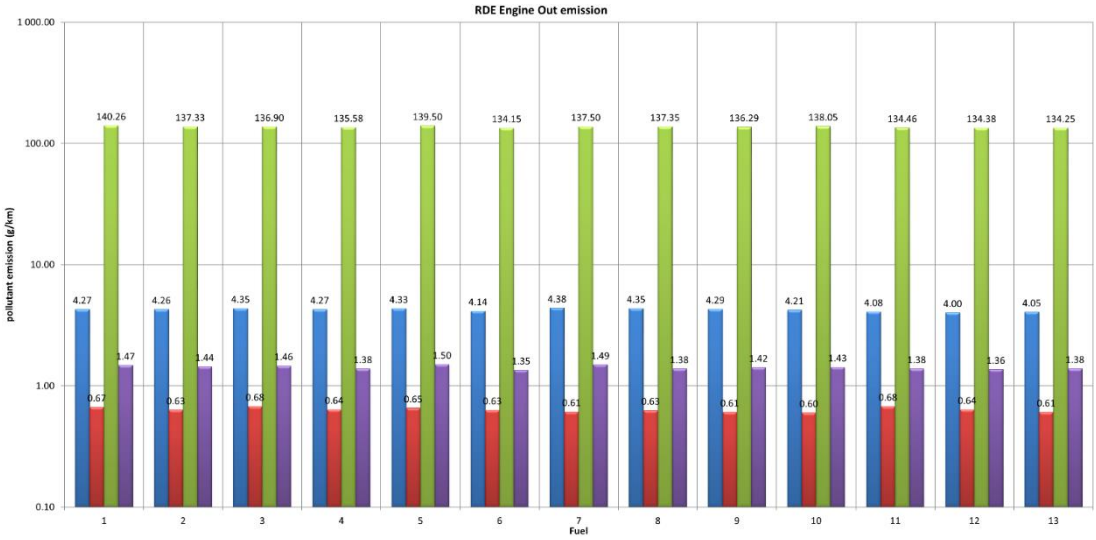


Figure 4.15 RDE cycle engine-out emissions for each of the test fuels (in g/km)

5. PHASE 1 - SCOPE OF STATISTICAL ANALYSIS

The test programme has generated a vast amount of data and the statistical analysis has been concerned with only a subset of this data. The statistical analysis has also focussed on the fuel properties in the designed matrix: E150, total aromatics, oxygenates, (<C9) aromatics and (≥C9) aromatics as these were the properties that the programme was designed to investigate the effect of.

The primary focus of the study was PN emissions upstream (engine-out) and downstream (tailpipe) of the GPF and the following measurements were studied:

Table 5.1 Scope of statistical analysis related to PN emissions

Measurement	**Test Cycle**		
	WLTC Cold	WLTC Hot	RDE
SPCS PN Full cycle	✓	✓	✓
Tail Pipe (TP) SPCS Phase 1	✓	✓	
Tail Pipe (TP) SPCS Phase 4	✓	✓	
Tail Pipe (TP) ELPI Full cycle	✓	✓	
Tail Pipe (TP) ELPI PN Phase 1	✓	✓	
Tail Pipe (TP) ELPI Phase 4	✓	✓	
ELPI PN > 23nm	✓	✓	✓
Engine Out (EO) ELPI Full cycle	✓	✓	
Engine Out (EO) ELPI Phase 1	✓	✓	
Upstream Mean Concentration	✓	✓	✓
Downstream Mean Concentration	✓	✓	✓
Overall GPF filtration Efficiency = 1 - Downstream Mean Conc. / Upstream Mean Conc.	✓	✓	✓

In addition, the analysis also considered engine-out (EO) and tailpipe (TP) gaseous pollutant emissions: CO, HC and NOx emissions.

Measurement	**Test Cycle**		
	WLTC Cold	WLTC Hot	RDE
EO CO, HC, NOx Full cycle	✓	✓	✓
EO CO, HC, NOx Phase 1	✓		
TP CO, HC, NOx Full cycle	✓ Bag	✓ Bag	✓ EO Post
TP CO, HC, NOx Phase 1	✓		

6. PHASE 1 - DATA QUALITY ASSESSMENT FOR STATISTICAL ANALYSIS

6.1. FAILED TESTS AND OMITTED DATA

The following table summarises the tests and measurements that have been omitted from the analysis. The table is concerned only with the variables listed in the afore-mentioned section on scope. Note that from Test 10 onwards, the actual test numbers differ from the original design of test sequence as a repeat of the failed test 9 (fuel 9) was carried out at this point.

Table 6.1 Omitted tests and data and related arguments

Block	Test	Cycle	Fuel	Measurements affected	Comment
1	1	All	9	Complete test	Without Stop Start
1	9	All	9	Complete Test	Without Stop Start. Repeated immediately as Test 10
1	3	WLTC Cold	12	Upstream Mean Concentration, Overall Efficiency & EO ELPI all cycle phases. All other measurements retained	An additional WLTC Cold repeat run in Block 3 Test 43
2	17	WLTC Cold	2	All WLTC Cold cycle	Stop Start problem WLTC Cold cycle repeat at end of Block 3 Test 47
3	30	RDE	3	All RDE cycle	Non-conforming Test. RDE cycle repeated at end of Block 3 Test 45
3	33	RDE	8	All RDE cycle	Start of Lockdown - RDE cycle not run. Complete retest of Fuel 8 (all cycles) Test 34 run at restart after lockdown
3	37	WLTC Cold	13	Upstream Mean Concentration, Overall Efficiency & EO ELPI all cycle phases All other measurements retained	Extreme outlier in Upstream Mean Concentration omitted following discussions with CERTAM 7/7/20
2	18	RDE	9	SPCS PN	Extreme outlier in PN omitted following discussions with CERTAM 7/7/20
3	34	WLTC Hot	8	EO_ELPI: Full cycle and all phases TP_ELPI: Full cycle and all phases	Very high value in Phase 1 affecting full cycle. Other phases omitted for consistency because full cycle omitted
1	8	RDE	1	EO HC	Extreme low value flagged by CERTAM in the summary file.

The extreme outliers are illustrated in the figures below.

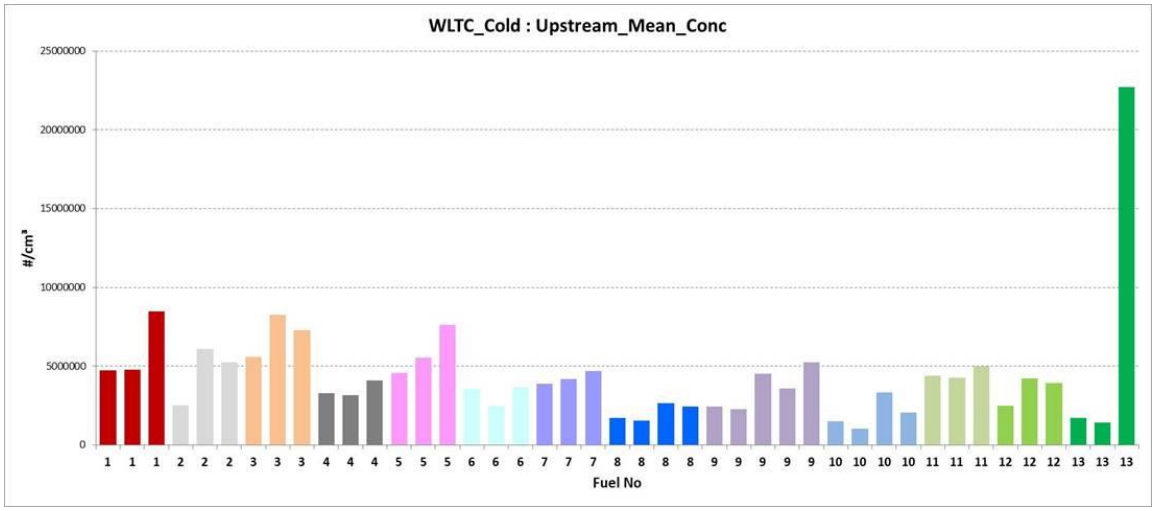


Figure 6.1 Illustration of the omitted outlier on the particulates engine-out mean concentration measured on the cold WLTC: Fuel 13, 3rd repeat

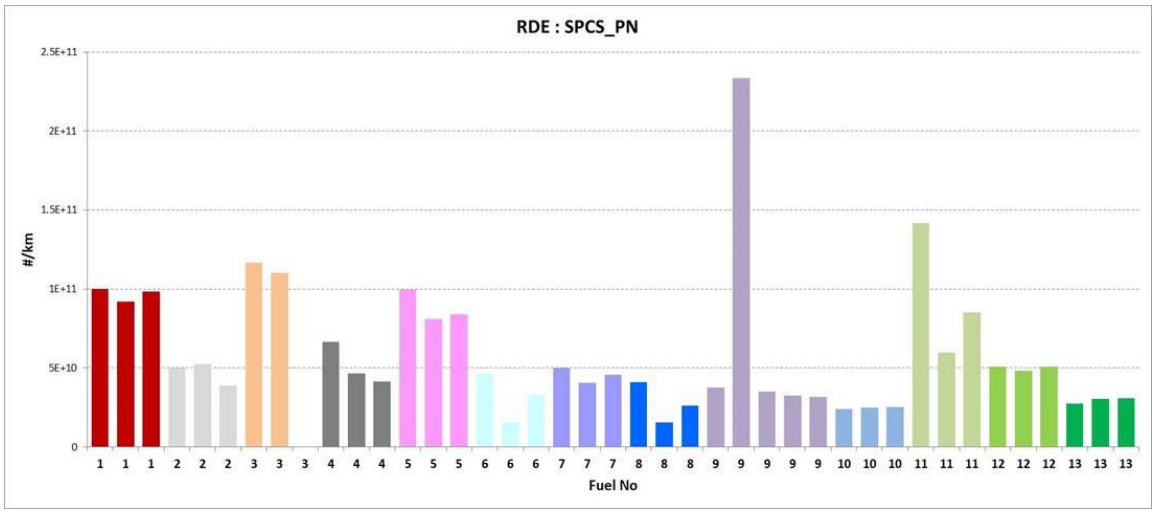


Figure 6.2 Illustration of the omitted outlier on the TP PN emissions measured by the SPCS on the RDE cycle: Fuel 9, 2nd repeat

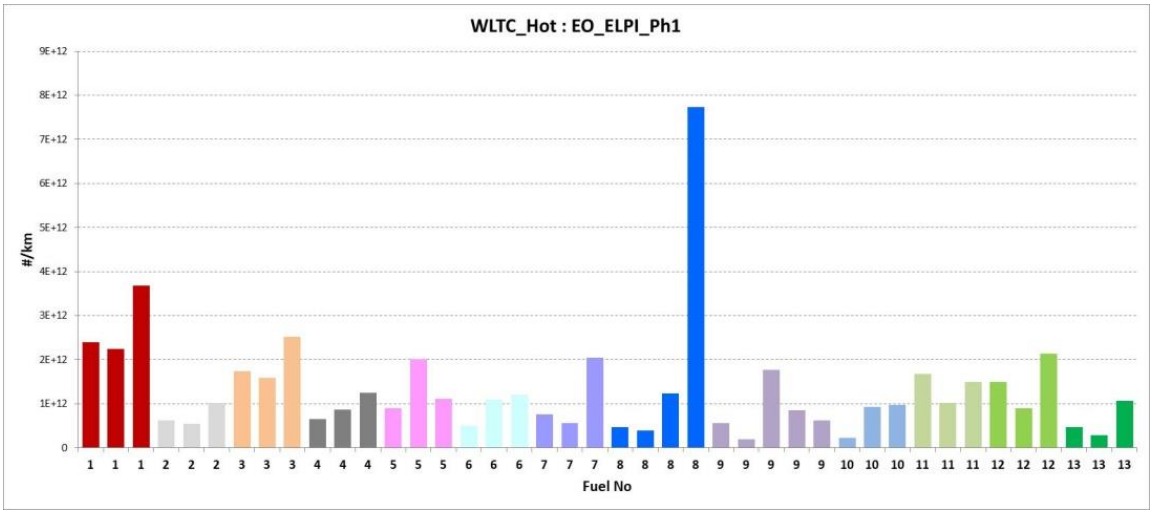


Figure 6.3 Illustration of the omitted outlier on the EO PN emissions measured by the ELPI on the 1st phase of the hot WLTC: Fuel 8, 4th repeat

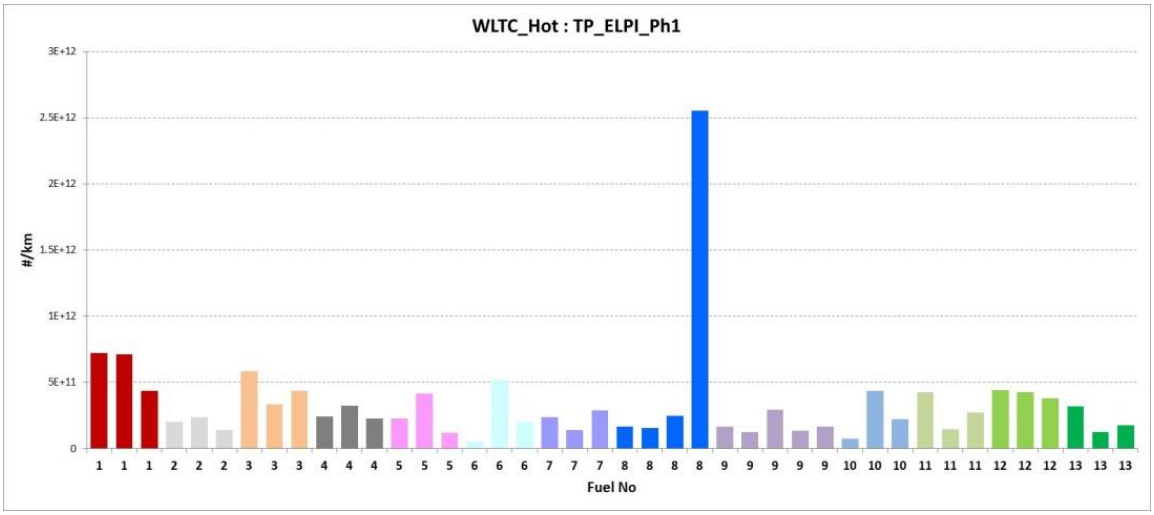


Figure 6.4 Illustration of the omitted outlier on the TP PN emissions measured by the ELPI on the 1st phase of the hot WLTC: Fuel 8, 4th repeat

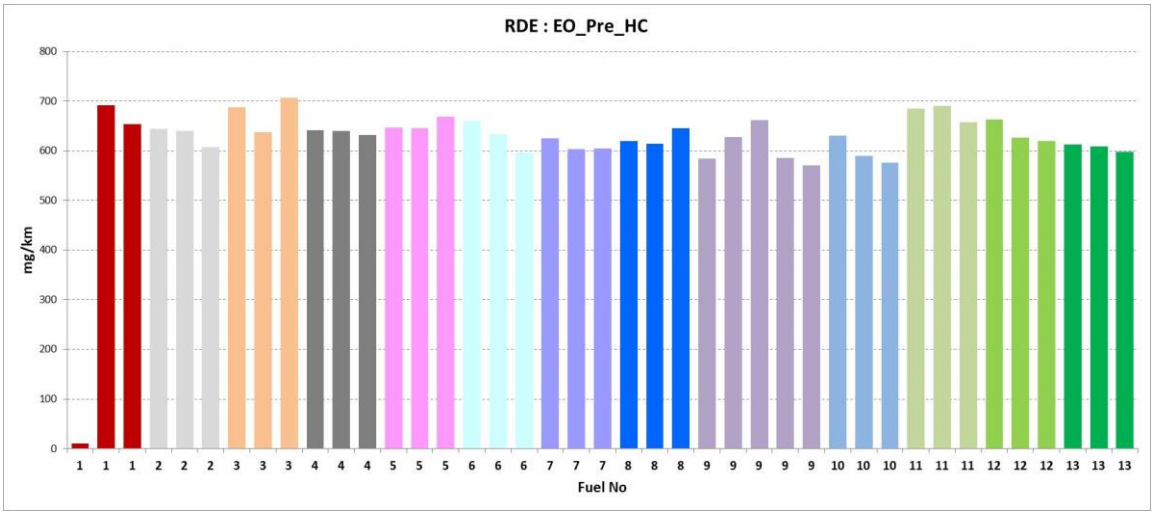


Figure 6.5 Illustration of the omitted outlier on the EO HC emissions measured on the RDE cycle: Fuel 1, 1st repeat

The actual test order is tabulated below. At the end of the test sequence, the order varies with test cycle as repeats were only carried out on the test cycle that originally failed.

Table 6.2 Actual test order

BLOCK 1				BLOCK 2				BLOCK 3			
Actual Test No			Fuel	Actual Test No			Fuel	Actual Test No			Fuel
Cold	Hot	RDE		Cold	Hot	RDE		Cold	Hot	RDE	
1			Fuel 9	16			Fuel 10	30			Fuel 3
2			Fuel 11	17			Fuel 2	31			Fuel 4
3			Fuel 12	18			Fuel 9	32			Fuel 5
4			Fuel 6	19			Fuel 8	33			Fuel 8
5			Fuel 7	20			Fuel 1	34			Fuel 8
6			Fuel 3	21			Fuel 4	35			Fuel 11
7			Fuel 10	22			Fuel 13	36			Fuel 9
8			Fuel 1	23			Fuel 12	37			Fuel 13
9			Fuel 9	24			Fuel 7	38			Fuel 7
10			Fuel 9	25			Fuel 6	39			Fuel 2
11			Fuel 5	26			Fuel 5	40			Fuel 6
12			Fuel 13	27			Fuel 9	41			Fuel 1
13			Fuel 2	28			Fuel 3	42			Fuel 12
14			Fuel 4	29			Fuel 11	43			Fuel 12
15			Fuel 8					44	43	43	Fuel 10
								45	44	44	Fuel 9
								46			Fuel 10
								47			Fuel 2
										45	Fuel 3

6.2. REPEAT TEST VARIABILITY

6.2.1. Data transformation

All PN measurements exhibit increased variation as the value of the measurement itself increases and have been analysed on the $\log_e$ scale in line with previous Concawe studies on diesel PN emissions. When backtransformed to the original scale, fuel means are therefore geometric means and not the arithmetic means of the raw data.

Overall GPF filtration efficiency values are generally in the 50%-100% range and show a clear reduction in variability as values get closer to 100%. Overall GPF filtration efficiency has been analysed using a simple $Log_e(1-X)$ transformation.

All statistical analysis has been carried out on the transformed scale.

6.2.2. Weighting

Tailpipe pollutant emissions (CO, HC & NOx) exhibit variation that increases with the value of the mean. Fuel means for pollutant emissions are usually presented on the raw scale for ease of comparison with emissions standards. For tailpipe emissions, this is achieved by a weighted analysis where the weights are equivalent to $1/(\text{Fitted Value})^2$. Engine-out pollutant emissions have been analysed unweighted.

6.3. LINEAR TRENDS IN THE DATA

6.3.1. Trends in TP PN emissions

The PN measurements TP SPCS PN and TP ELPI PN (Full, Phase 1 & Phase 4) measurements all show a downward trend to a greater or lesser extent in all cycles. As this can be explained as a real physical effect (the filtration efficiency of GPFs is known to increase with mileage, due to its progressive clogging by non-combustible exhaust components), it was deemed justifiable to correct the data for the trends in these variables. To maintain a consistent approach, a trend correction has been applied to these variables in all cycles regardless of the level of statistical significance. Correcting for a non-significant trend has negligible effect on the data and hence does not cause any difficulty.

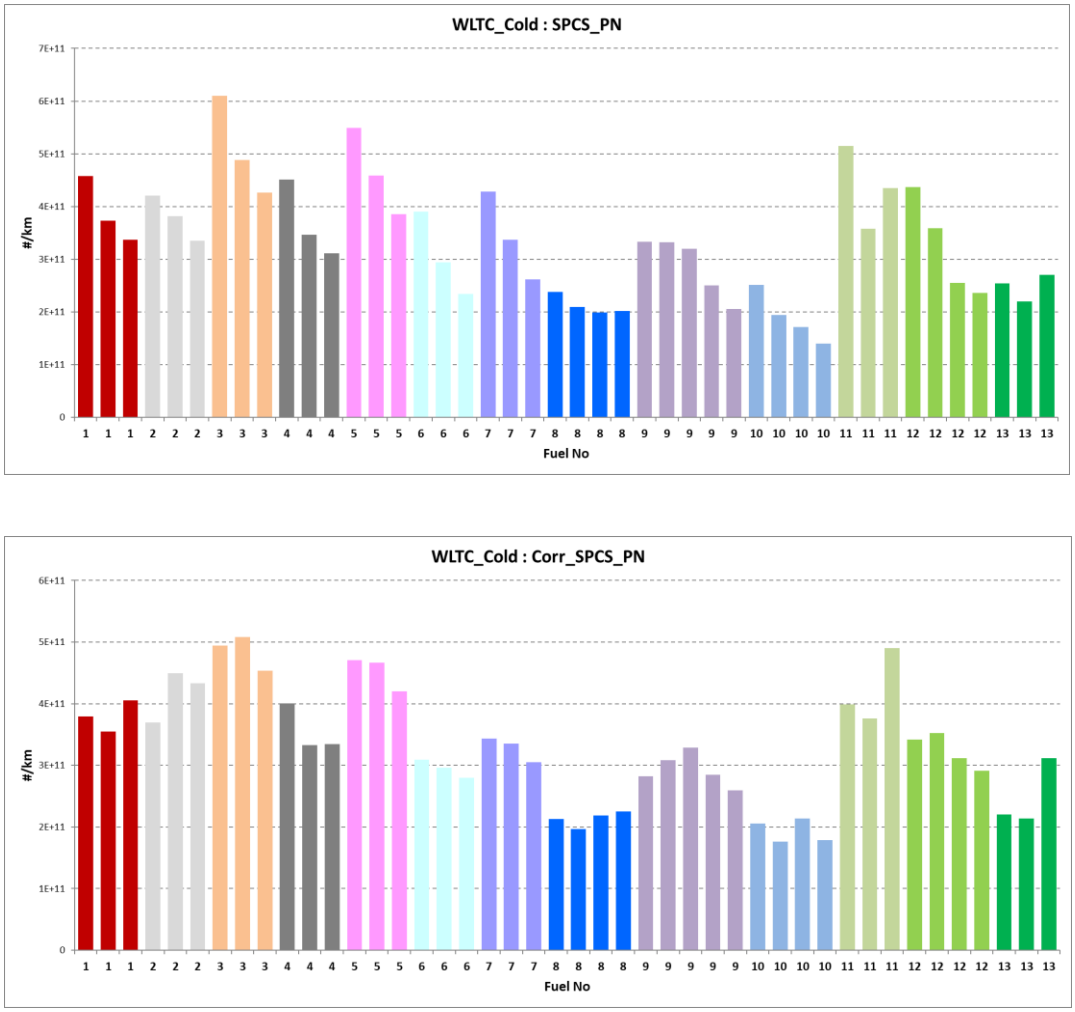


Figure 6.6 Top: Non-corrected TP SPCS PN emissions on the cold WLTC, ordered by fuel number and by test number. A downward trend for each of the fuels can clearly be observed. Bottom: Corrected TP SPCS PN emissions, succeeding in removing the trend effect.

Downward trends were also seen in the gaseous engine-out emissions for HC & NOx again in all test cycles and these have likewise been corrected RDE cycles.

Trends are estimated in the software package by fitting a model in Fuel and Test number. The actual test number, which includes invalid tests has been used to estimate the trends. This is appropriate because it is vehicle usage that correlates with the trend so invalid tests should be counted in the sequence. Once the trend has been estimated, trend corrections are made externally to the analysis about the mid-point of the sequence from Test No = 2 (first valid test) to the final test. Statistical analysis is subsequently carried out on the trend-corrected data.

The test sequence has been designed to be robust to correction for a linear trend. The average position of each fuel in the sequence was close to the mid-point and the fuel means will be minimally changed by the correction except where repeats of failed tests have been added at the end of the sequence. The main benefit of correcting for the trend is that it removes a significant and identifiable element of

the random repeat test-to-test variation. This in turn leads to a more discriminating analysis with an improved chance of detecting significant fuel effects.

Applying the correction externally ensures that it is applied at the exact mid-point of the test sequence and, once applied, the corrected variable is available for visualisation and comparison with the uncorrected variable. It also ensures that the trend is estimated solely from the residual repeat test error (after removing fuel differences) and does not vary depending on the fuel properties in the model, which would be the case if it was fitted as an additional parameter in the fuel property modelling process. Applying the correction externally does however introduce two small errors:

- the degrees of freedom for the corrected variable are the same as for the uncorrected variable when theoretically they should be one less. Since this is a difference of ~30 degrees of freedom versus ~29 degrees of freedom, any error introduced here has a negligible effect on the subsequent analysis.

- the standard error of the fuel means, and other estimated parameters do not include the component associated with estimating the trend correction and these will be very slightly smaller than they should be. However, this effect is extremely small and will not impact the conclusions of the study.

The trend corrections are detailed in the following tables for reference. All trends are on the $\log_e$ scale for PN measurements and the raw scale for pollutant emissions. In the tables, the P-value is the significance level of the trend. The two values of R^2 that are given are interpreted as follows:

- "R^2 Before" corresponds to the proportion of the variation in the data explained by the 13 fuels using the uncorrected data i.e. before correction for the trend.

- "R^2 After" corresponds to the proportion of the variation in the data explained by the 13 fuels using the corrected data i.e. after correction for the trend.

Where the trend is highly significant, the impact on R^2 is greatest. The R^2 value is the proportion of the variation explained by differences between the 13 fuels i.e. it is the R^2 for the model containing just "Fuel" as a factor. Where the trend is only marginally significant (or rarely where it is not significant at all but has been corrected for to maintain consistency), the correction will have negligible impact and the corrected measurements will be virtually identical to the uncorrected measurements.

Table 6.3 Parameters of trends in TP PN emissions and results of trends correction on cold WLTC

WLTC Cold	SPCS PN		TP SPCS Ph1		TP SPCS Ph4	
Trend estimated value	-0.011336		-0.010605		-0.01253	
P-Value	<0.0001		<0.0001		0.0167	
R^2 Before | After	0.75	0.92	0.69	0.87	0.66	0.69

WLTC Cold	TP ELPI Full		TP ELPI Ph1		TP ELPI Ph4	
Trend estimated value	-0.009538		-0.007334		-0.013661	
P-Value	0.0003		0.0135		0.0046	
R^2 Before | After	0.58	0.66	0.47	0.50	0.70	0.73

WLTC Cold	ELPI PN>23nm	
Trend estimated value	-0.008191	
P-Value	0.0001	
R^2 Before | After	0.76	0.83

Table 6.4 Parameters of trends in TP PN emissions and results of trends correction on hot WLTC

WLTC Hot	SPCS PN		TP SPCS Ph1		TP SPCS Ph4	
Trend estimated value	-0.002776		0.008277[2]		-0.014545	
P-Value	Not Sig.		0.0960		0.0056	
R^2 Before | After	0.89	0.89	0.59	0.62	0.82	0.86

WLTC Hot	TP ELPI Full		TP ELPI Ph1		TP ELPI Ph4	
Trend estimated value	-0.01073		-0.00048		-0.02061	
P-Value	0.0056		Not Sig.		0.0021	
R^2 Before | After	0.82	0.86	0.46	0.46	0.72	0.79

WLTC Hot	ELPI PN>23nm	
Trend estimated value	-0.007698	
P-Value	0.0373	
R^2 Before | After	0.87	0.88

Table 6.5 Parameters of trends in TP PN emissions and results of trends correction on RDE cycle

RDE	SPCS PN		ELPI PN>23nm	
Trend estimated value	-0.005499		-0.011415	
P-Value	0.0786		<0.0001	
R^2 Before | After	0.86	0.87	0.84	0.91

6.3.2. Trends in engine-out gaseous pollutant emissions

Linear trends in EO gaseous pollutant emissions are estimated on the raw scale.

Table 6.6 Parameters of trends in EO gaseous pollutant emissions and results of trends correction on cold WLTC

WLTC Cold	Engine Out HC				Engine Out NOx			
	Full Cycle		Phase 1		Full Cycle		Phase 1	
Trend estimated value	-1.3236		-1.3236		-6.1655		-6.2628	
P-Value	0.0001		0.0001		<0.0001		<0.0001	
R^2 Before | After	0.72	0.80	0.75	0.82	0.17	0.51	0.16	0.62

[2] slightly positive and significant only at 90% Conf (P<0.1)

Table 6.7 Parameters of trends in EO gaseous pollutant emissions and results of trends correction on hot WLTC

WLTC Hot Full Cycle	Engine Out HC		Engine Out NOx	
Trend estimated value	-0.6736		-6.3026	
P-Value	0.0152		<0.0001	
R^2 Before | After	0.74	0.77	0.18	0.54

Table 6.8 Parameters of trends in EO gaseous pollutant emissions and results of trends correction on RDE cycle

RDE	Engine Out HC		Engine Out NOx	
Trend estimated value	-0.7355		-3.8196	
P-Value	0.0154		<0.0001	
R^2 Before | After	0.62	0.68	0.38	0.63

6.4. STEP CHANGE IN PN MEASUREMENTS AND OVERALL EFFICIENCY

A step change increase in the Upstream (engine-out) Mean PN Concentration measurements can be observed in all three test cycles. It is also seen in the EO ELPI Full and EO ELPI Phase 1 data.

There is a corresponding step decrease in the Downstream (tailpipe) Mean PN Concentration measurements. Both changes occur in Block 2 approximately in the region of Tests 25 & 26 (Fuels 6 & 5). This behaviour in both Upstream and Downstream Mean Conc. feeds through into the calculation of Overall GPF filtration Efficiency which also exhibits a shift in levels at a similar point in Block 2.

There is no identifiable explanation of this shift in the results and nor it is clear at exactly which point in the sequence it occurred. As there is no physical justification on which to base a correction to the data or any surety of the exact point of occurrence, it was decided not to apply any correction to the data. Measurements exhibiting the step change have therefore been analysed without any correction being applied.

There are two drawbacks to not correcting for this step change:

- The fuels are not balanced either side of the step: some fuels were tested twice before it and once after and other fuels were tested once before it and twice afterwards. Hence, the fuels are not all on an equal basis for the purposes of further analysis and it is possible that the subsequent statistical analysis could yield misleading conclusions.

- The step will be included in the random variation of the data and will greatly inflate it thus reducing the statistical power to detect significant fuel effects.

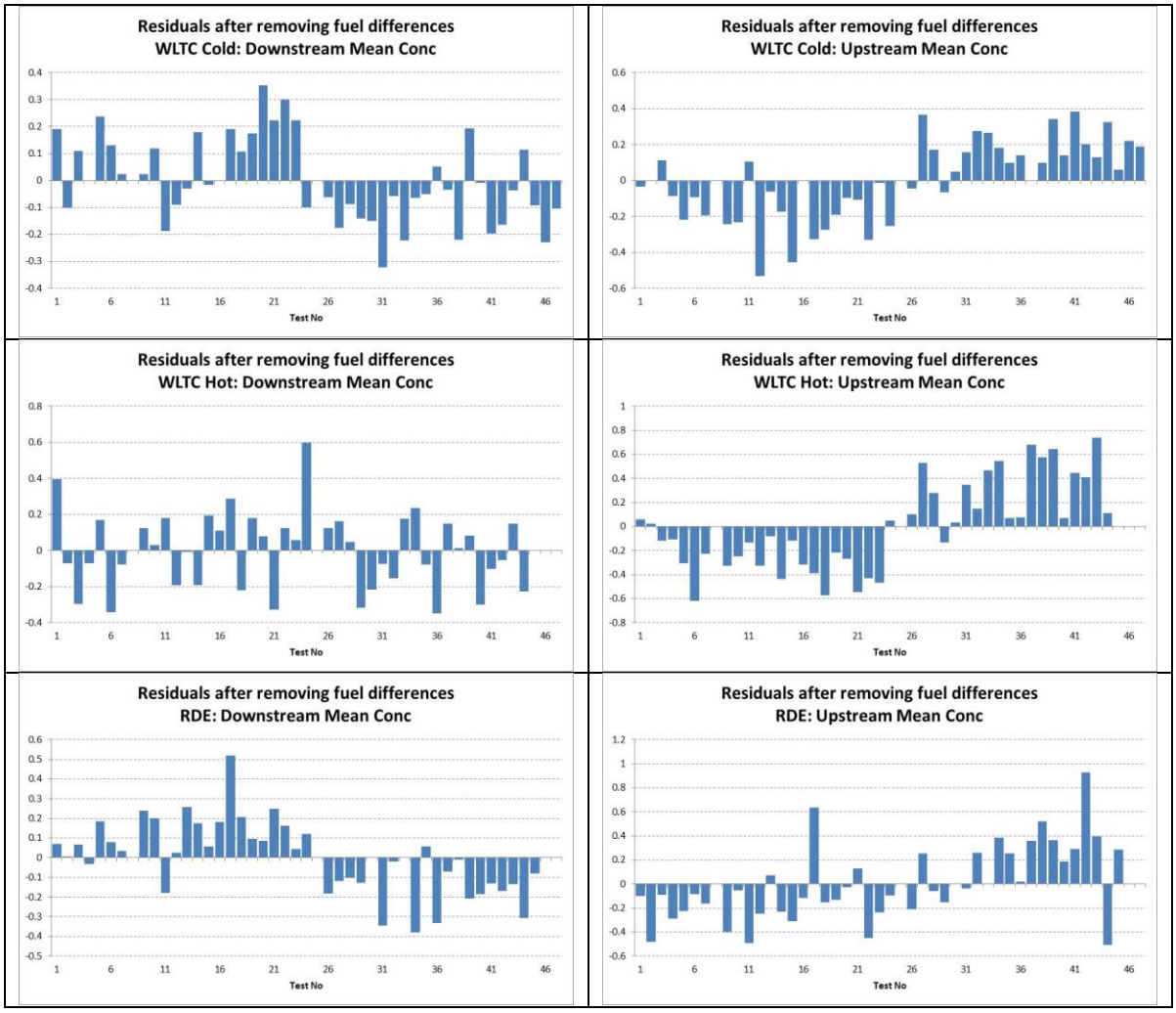


Figure 6.7 Residuals (Log_e scale) for Downstream and Upstream Mean PN Concentration. A step change can be observed in Block 2 in all cases except Downstream Mean Conc. in the WLTC hot cycle

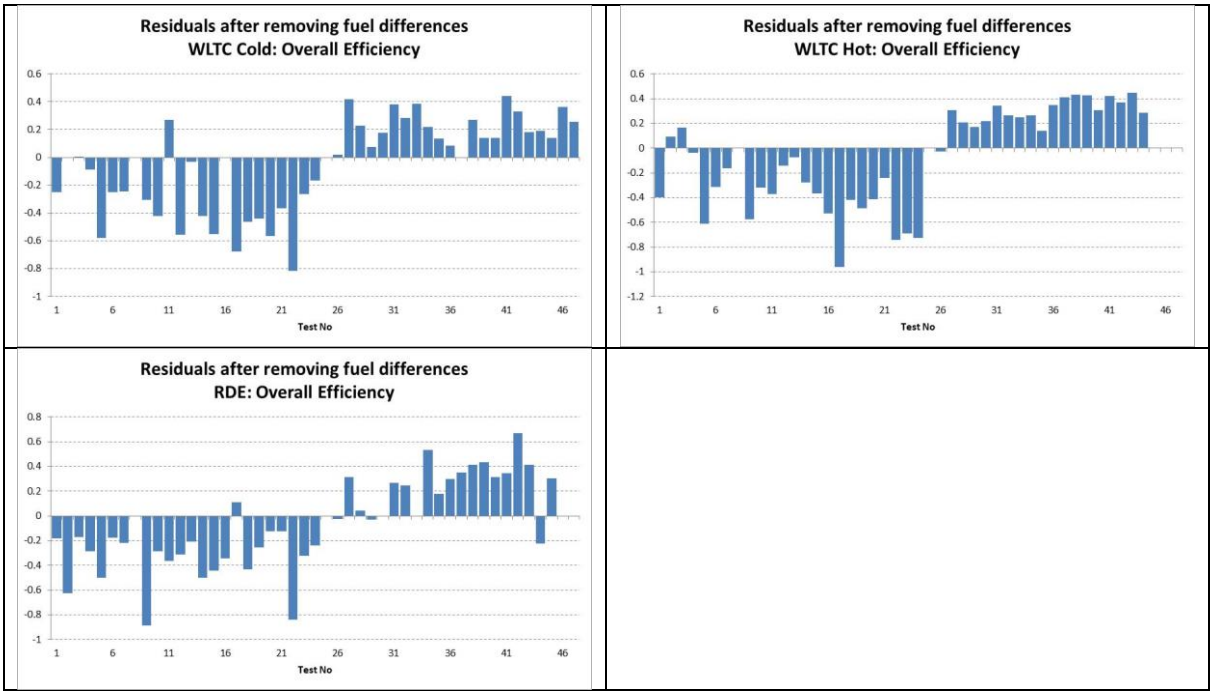


Figure 6.8 Residuals (transformed scale) for overall GPF filtration efficiency. The step change can be observed in Block 2 along with a noticeable downward trend in the WLTC cycles before the step

6.5. BEHAVIOUR OF TAIL PIPE HC AND NOX (RDE CYCLE)

Tailpipe HC and NOx emissions both showed a group of higher measurements towards the end of the test sequence in Block 3. These can be seen in the residuals after fitting Fuel in the figure below. There is no explanation for these higher measurements, and they have been accepted as part of the random variation in the data

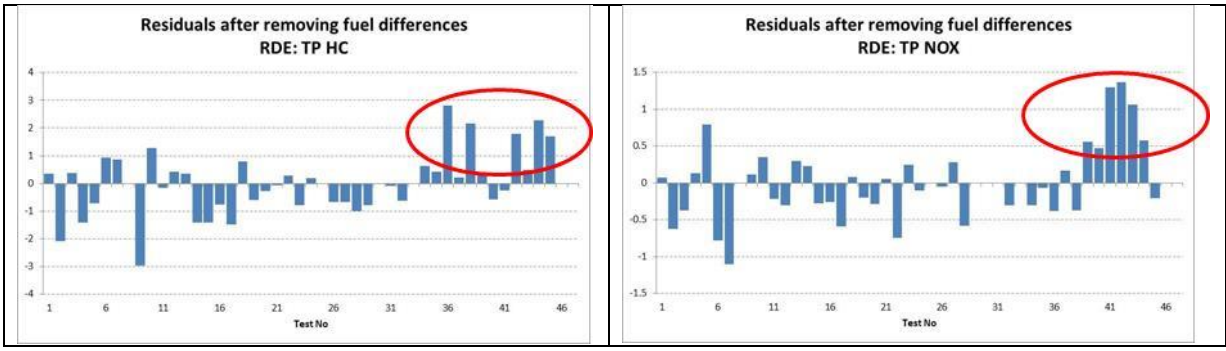


Figure 6.9 Residuals for Tailpipe HC and NOx emissions showing a batch of high values towards the end of the test sequence

6.6. INTERRUPTION TO TESTING DUE TO LOCKDOWN

The test sequence was paused for a period of approximately 6 weeks as a result of lockdown during the coronavirus pandemic. The interruption occurred after the

WLTC Hot cycle in Test 33 (Fuel 8), Block 3. When testing resumed, Fuel 8 WLTC Cold and Hot cycles were repeated again. There was no evidence in the key measurements of interest that the interruption has had a material impact on the results and hence there has not been any need to apply any correction for the lockdown interruption.

6.7. TEST DRIVERS

In a test programme of this length, it is not practical to expect that the test facility can ensure the same driver is available to drive all tests on all fuels on the same test cycle and some mixing of different drivers is inevitable. All test drivers are expected to be professionally trained experts in driving the test cycle and so a consistent level of performance would normally be expected especially in the recognised WLTC test cycles. In the RDE cycle, driving style could potentially play a bigger role and it was important to check this. An attempt was made to check whether there was any difference in the results due to the different drivers. There was no consistent evidence that this was the case and the different drivers have been accepted as part of the underlying random variation.

7. PHASE 1 – STATISTICAL ANALYSIS METHODOLOGY

The data set for each cycle x measurement has been analysed separately. Some differences have been applied in the approach to the analysis for the different measurements considered and these are outlined below.

As this is a designed experiment with limited data and only 13 fuels, no attempt has been made to retain any subset of the data for validation purposes. All data has been used the modelling.

7.1. DATA TRANSFORMATION AND WEIGHTING

The standard statistical methods used in this study assume that variation is constant regardless of the value of the measurement. This assumption does not hold for PN measurements and for some tailpipe emissions measurements. In these cases, it is necessary to apply an appropriate data transformation or use a weighted analysis.

7.1.1. PN emissions measurements

As previously discussed, the variability of PN emissions measurements increases with their mean and they have been analysed on the $\log_e$-transformed scale in line with previous Concawe studies of PN measurements in diesel vehicles. The use of the $\log_e$-transformation for PN measurements has the advantage that the resulting fuel means will be geometric means and not the arithmetic means of the raw data. This is preferred for PN measurements, which can be highly variable, because arithmetic means can be dominated by one or two high values and hence be unrepresentative of the main body of data. All statistical analysis has been carried out on the transformed scale.

7.1.2. Overall GPF filtration efficiency

Overall GPF filtration efficiency shows a noticeable reduction in variability at levels closer to 100%. This is expected as high values close to the 100% ceiling have less scope to vary than more moderate mid-range values. With one exception (WLTC Cold test at 43%), all overall efficiency values are greater than 50%. Standard deviation versus mean plots shows linearly decreasing variability with the mean, hence a simple $\text{Log}_e(1\text{-}X)$ transformation is adequate to model the variability. It is not necessary to cater for different variability at the 0% end of the scale since there are no measurements in this region. All statistical analysis has been carried out on the transformed scale.

7.1.3. Gaseous pollutant emissions

It is common for gaseous pollutant emissions (CO, HC & NOx) to exhibit variation that increases with the value of the mean, and this is indeed seen in the tailpipe emissions. It is not evident in the engine-out emissions because these are much higher and, proportionally, the range of values over the 13 fuels is much less than for tailpipe emissions. Fuel means for pollutant emissions are usually presented on the raw scale for ease of comparison with emissions standards. For tailpipe emissions, this is achieved by an iteratively re-weighted analysis where the weights are equivalent to $1/(\text{Fitted Value from the previous iteration})^2$. 10 iterations are performed but, in practice adequate convergence is achieved after just a few iterations.

Engine out emissions have been analysed unweighted throughout.

7.2. FUEL MEANS

Fuel means are generated by fitting a model that has "Fuel" as a factor. All fuel means analyses have been carried out using the data transformation or weighting discussed above. Error bars on fuel means charts are 95% confidence intervals on the mean. They reflect the uncertainty in the mean due to random variation in repeat test measurements.

7.2.1. Cold WLTC

The three following figures show the consistency between corrected and uncorrected data, as far as the mean value is concerned. The beneficial aspect of trend correction can also be observed as the confidence intervals are reduced, providing more robust data. The second figure shows a good consistency between TP SPCS and ELPI PN emissions (having a diameter bigger than 23 nm), which is another way to demonstrate that the collected measurements provide robust data. Furthermore, a look at the scale of the third figure (compared to the first figure) shows that significantly more PN emissions occur during the 1st phase of the WLTC, corresponding to the cold start.

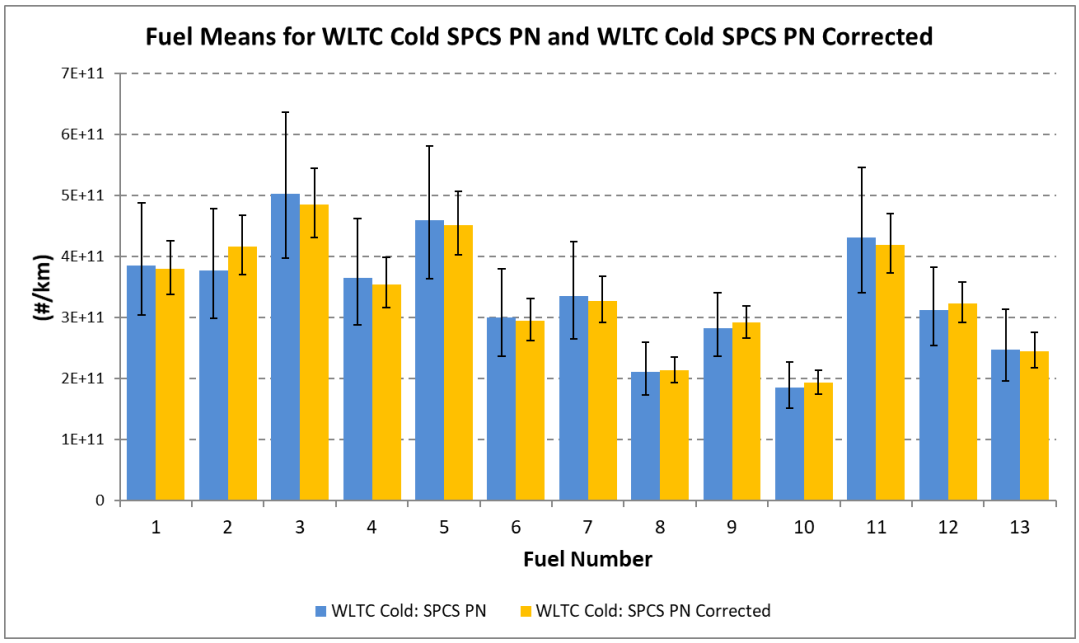


Figure 7.1 Comparison between uncorrected and corrected TP SPCS PN emissions on the cold WLTC.

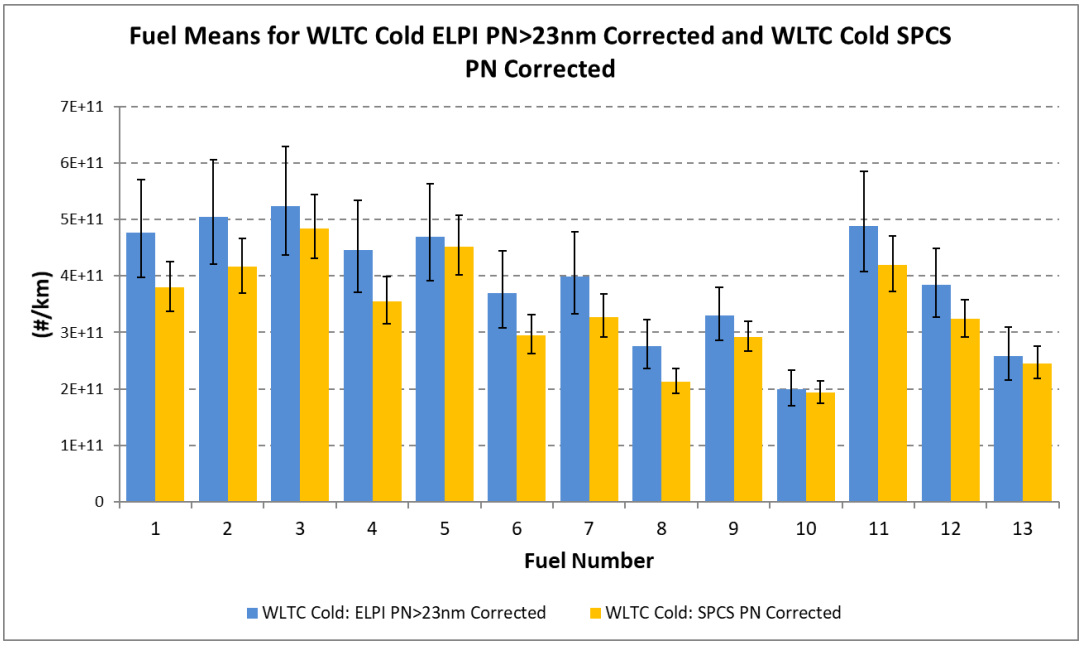


Figure 7.2 Comparison between corrected TP SPCS PN and corrected TP ELPI PN emissions having a diameter bigger than 23 nm on the cold WLTC.

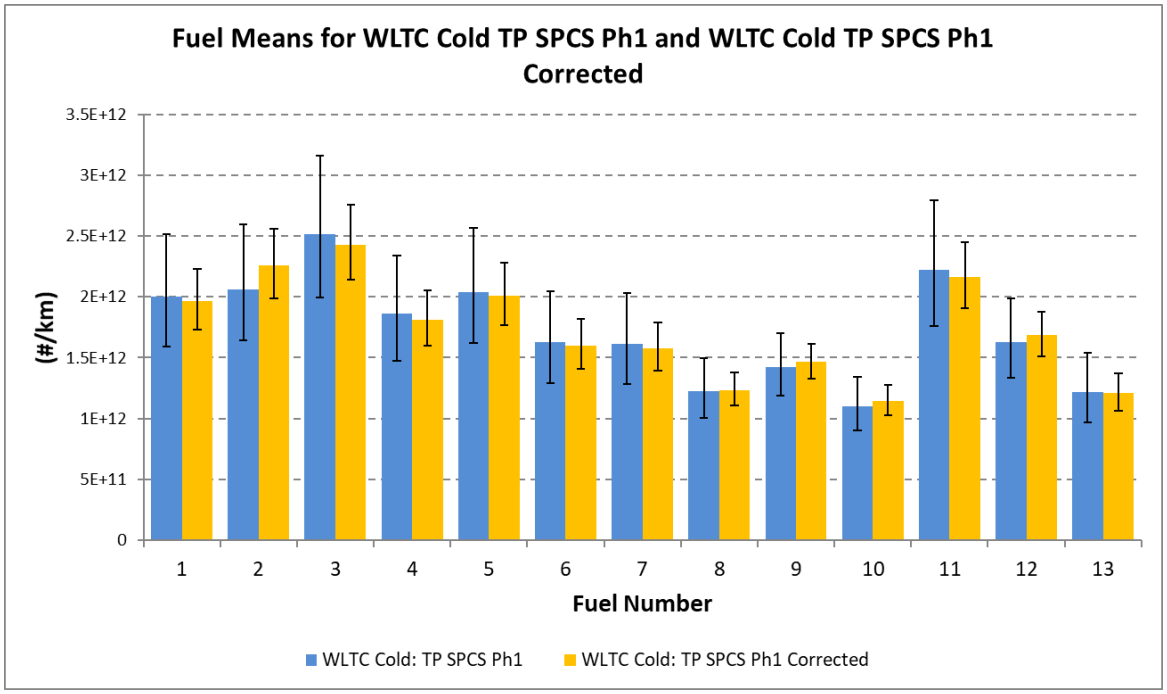


Figure 7.3 Comparison between uncorrected and corrected TP SPCS PN emissions on the 1st phase of the cold WLTC.

The figure below, showing a comparison between EO and TP ELPI PN emissions, illustrates the filtration efficiency of the GPF, which is provided as such in the following figure.

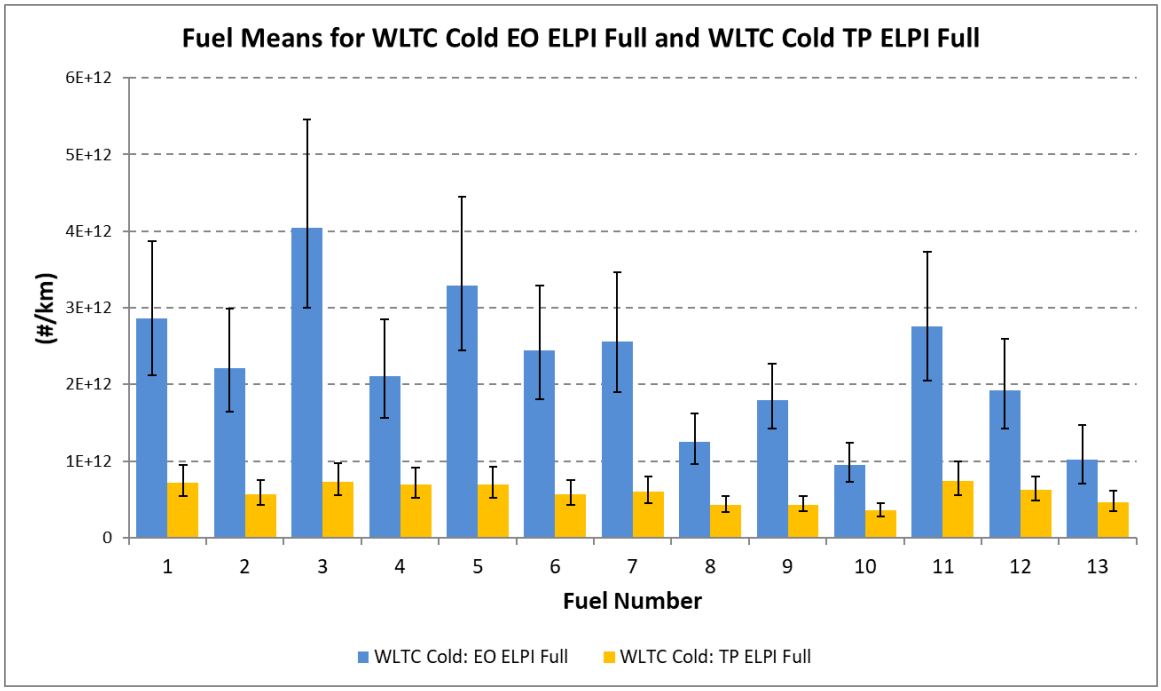


Figure 7.4 Comparison between EO and TP ELPI PN emissions having a diameter bigger than 23 nm on the cold WLTC.

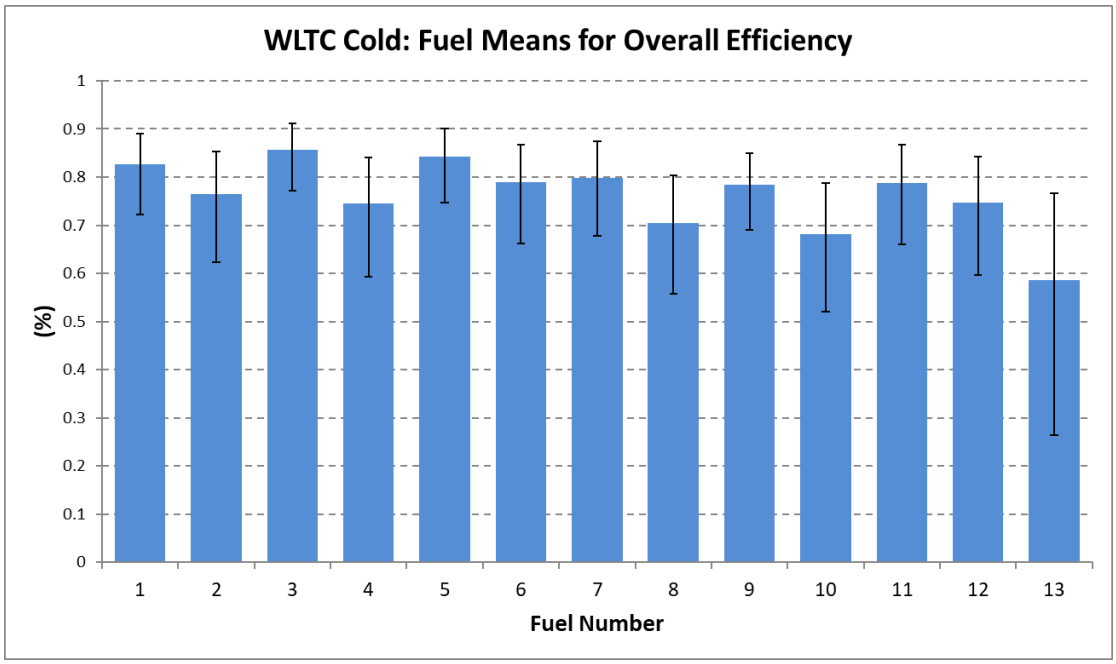


Figure 7.5 Overall GPF filtration efficiency on the cold WLTC.

7.2.2. Hot WLTC

The following figures show similar data as in the previous paragraph, but this time related to the hot WLTC. Similar conclusions as above can be drawn from these figures.

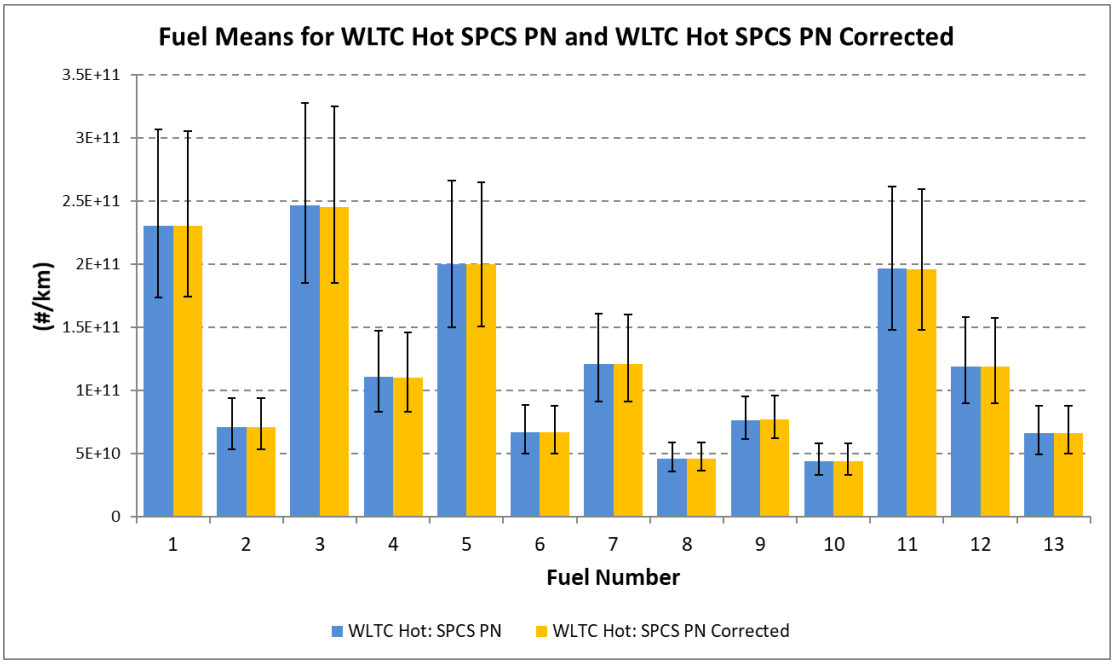


Figure 7.6 Comparison between uncorrected and corrected TP SPCS PN emissions on the hot WLTC.

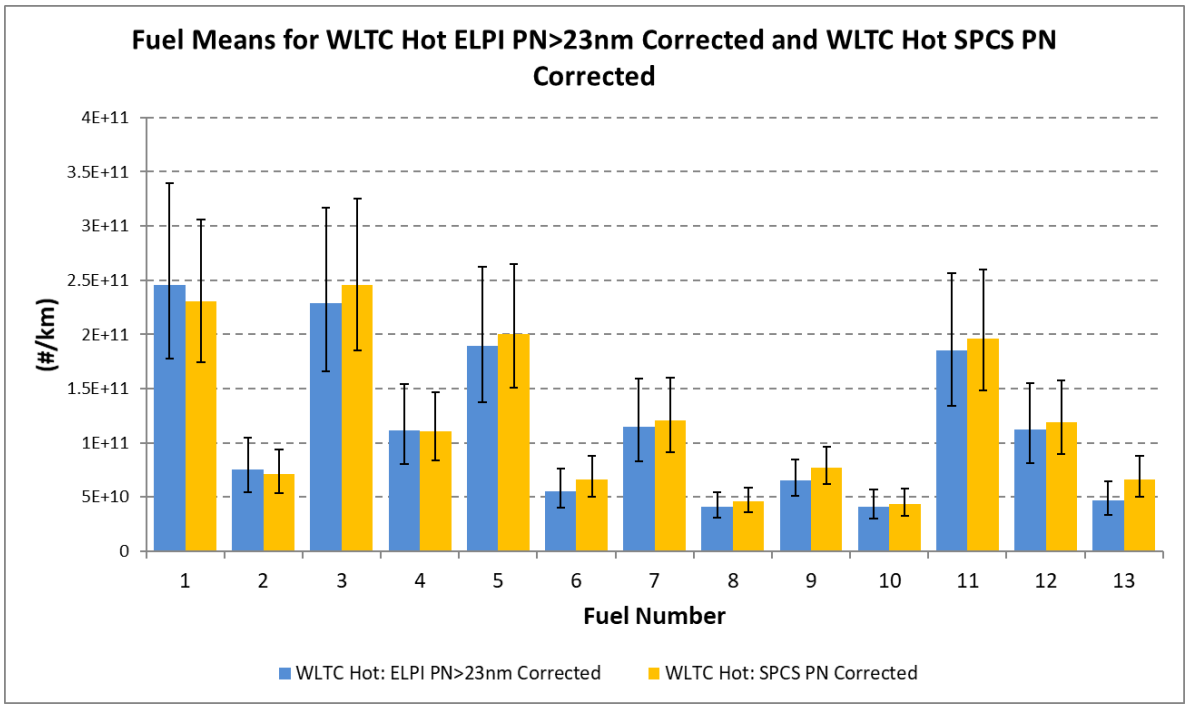


Figure 7.7 Comparison between corrected TP SPCS PN and corrected TP ELPI PN emissions having a diameter bigger than 23 nm on the hot WLTC.

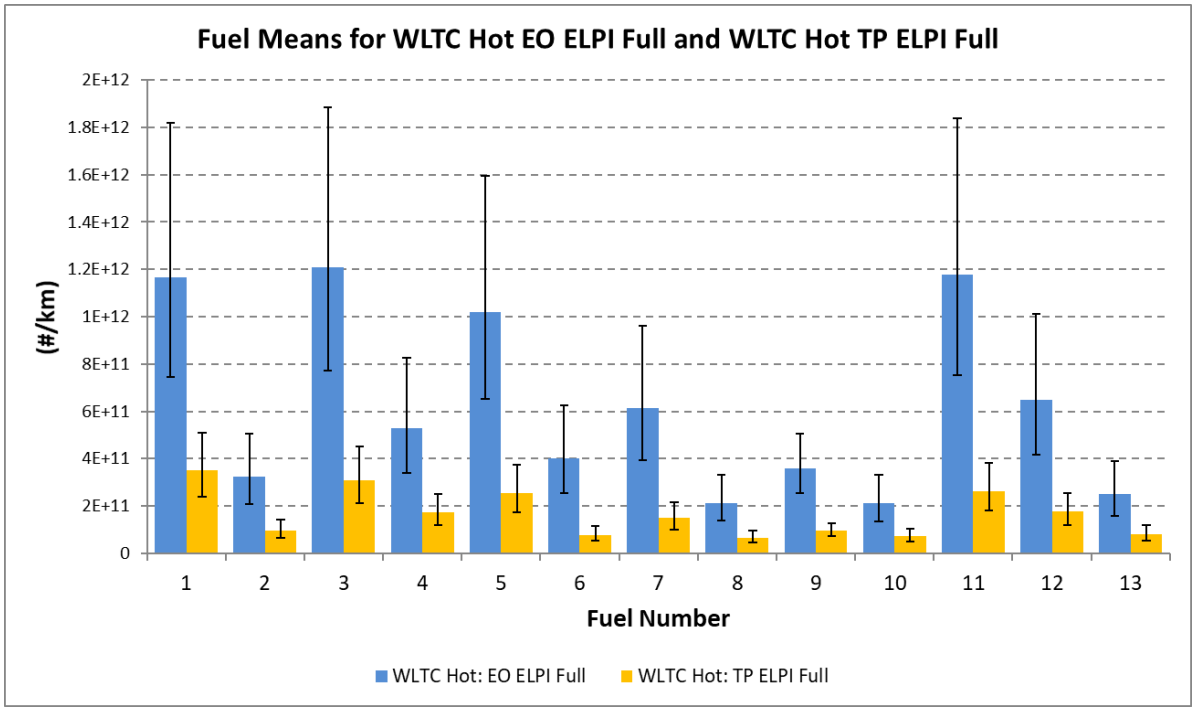


Figure 7.8 Comparison between EO and TP ELPI PN emissions having a diameter bigger than 23 nm on the hot WLTC.

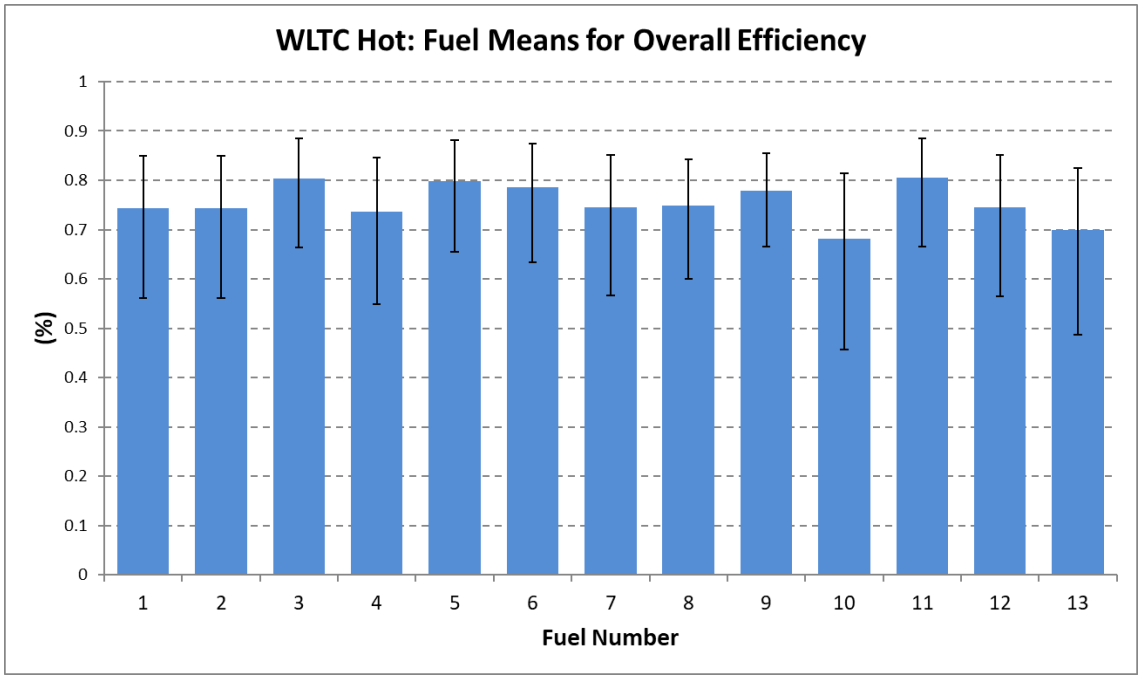


Figure 7.9 Overall GPF filtration efficiency on the hot WLTC.

7.2.3. Cold WLTC vs. Hot WLTC

The following figures provide a comparison of the cold and the hot WLTC. In the two first figures, it can be observed significantly higher TP and EO PN emissions

during the cold WLTC compared to the hot WLTC. The third figure shows that this is due to the contribution of the cold start, emitting much more PN emissions during the first phase compared to a hot start. Such a difference can no longer be observed during the fourth phase (fourth figure), as the powertrain has reached hot conditions independent on the initial temperature conditions at engine start. Finally, the fifth figure, showing the overall GPF filtration efficiency, shows that the filtration efficiency remained more or less constant, although the EO and TP were significantly different.

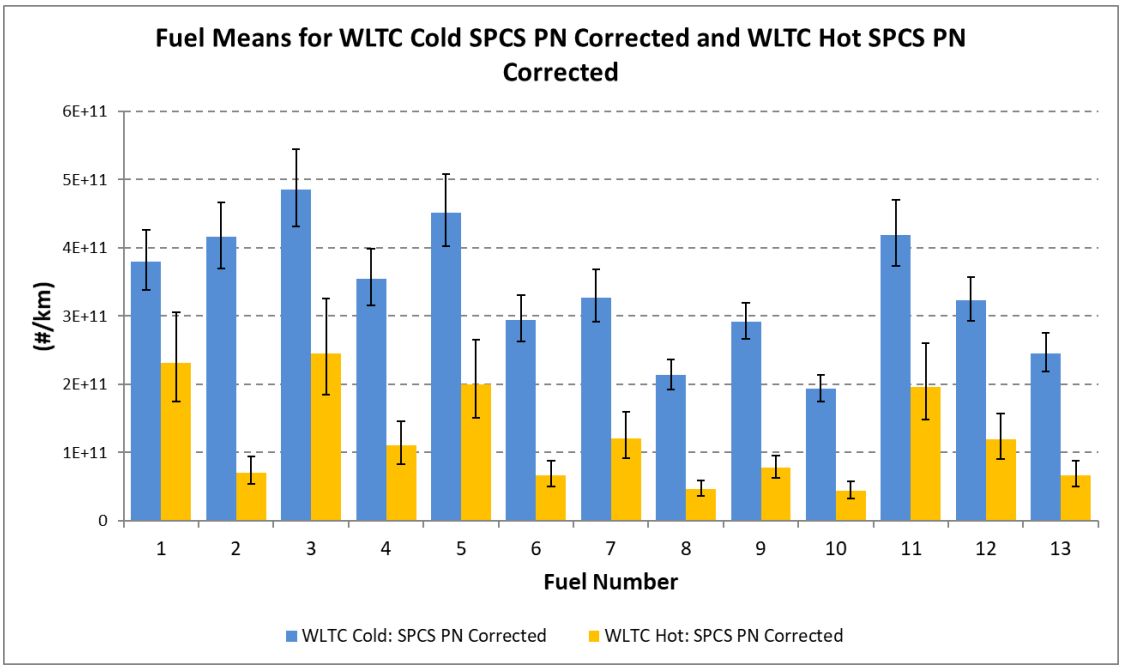


Figure 7.10 Comparison between cold and hot WLTC TP SPCS PN emissions.

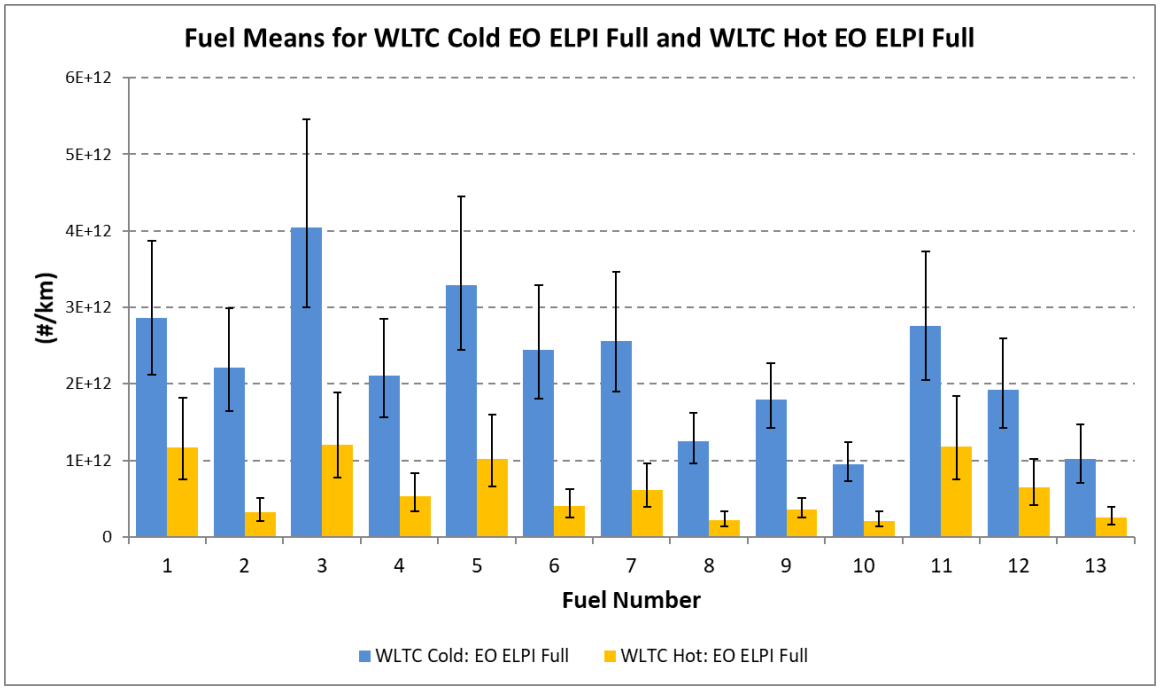


Figure 7.11 Comparison between cold and hot WLTC EO ELPI PN emissions.

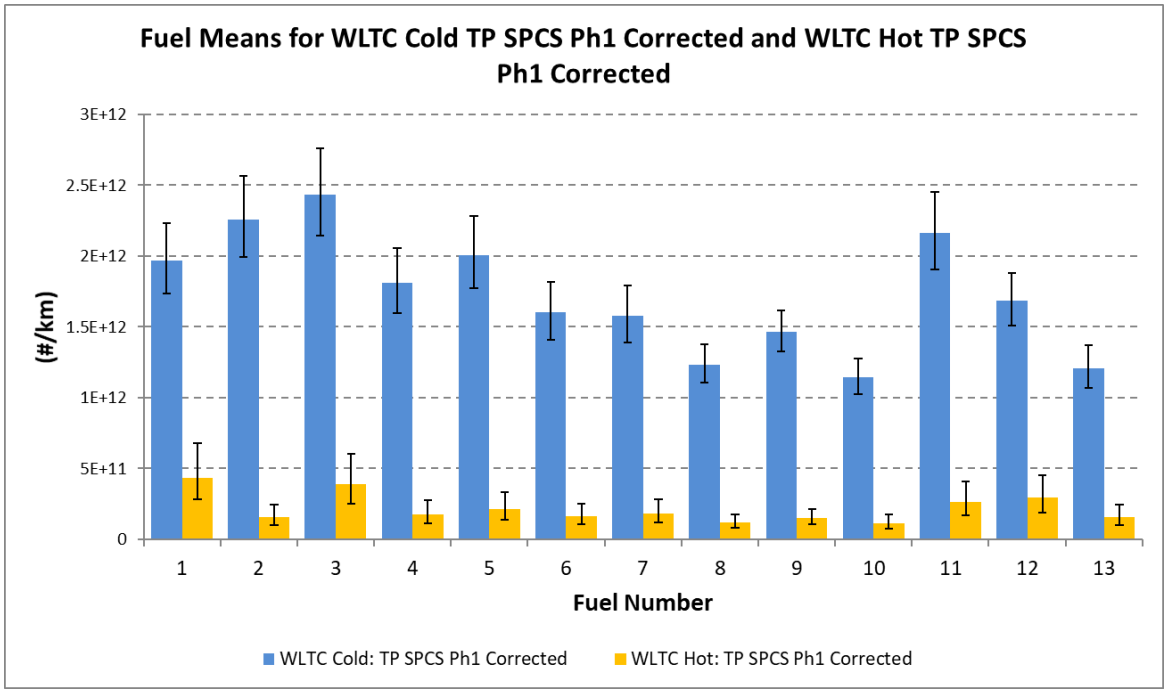


Figure 7.12 Comparison between cold and hot WLTC TP SPCS PN emissions during the 1st phase.

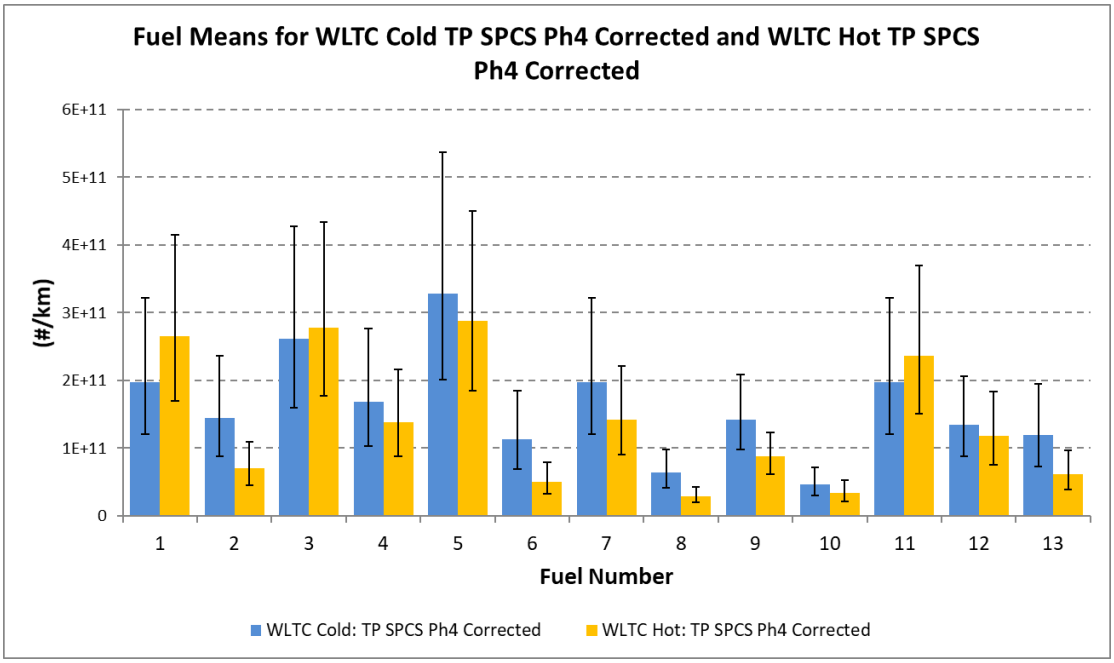


Figure 7.13 Comparison between cold and hot WLTC TP SPCS PN emissions during the 4th phase.

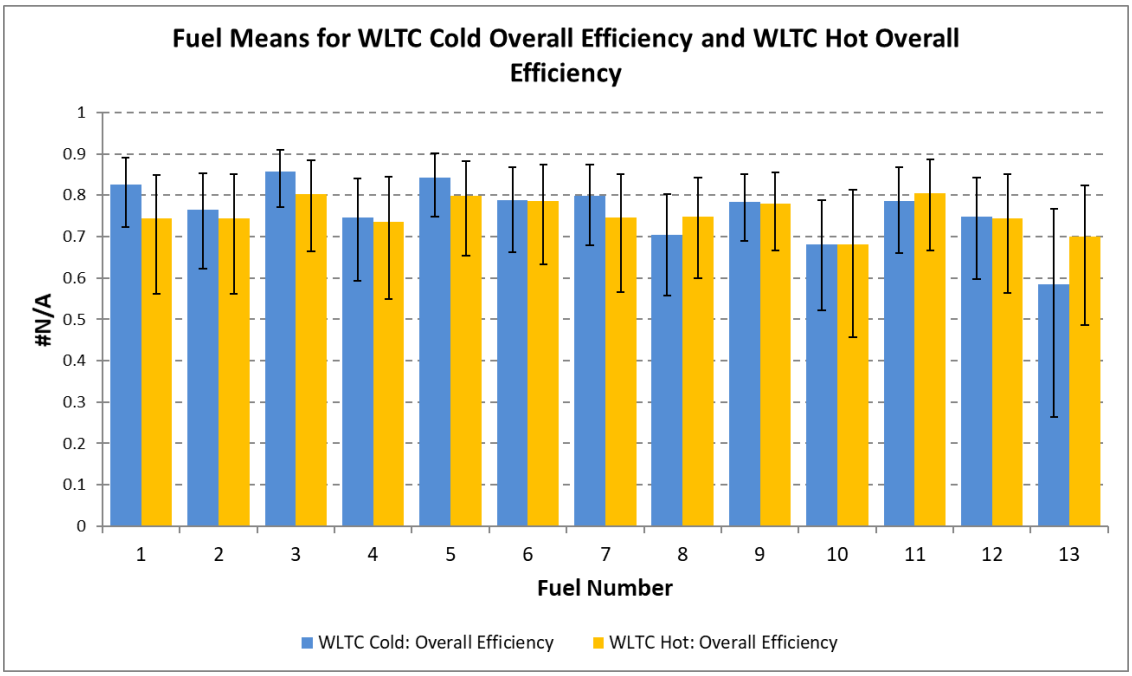


Figure 7.14 Comparison between cold and hot WLTC overall GPF filtration efficiency.

7.2.4. RDE cycle

The following figures show similar data as in the previous paragraphs, this time related to the RDE cycle. Similar conclusions as above can be drawn from these figures.

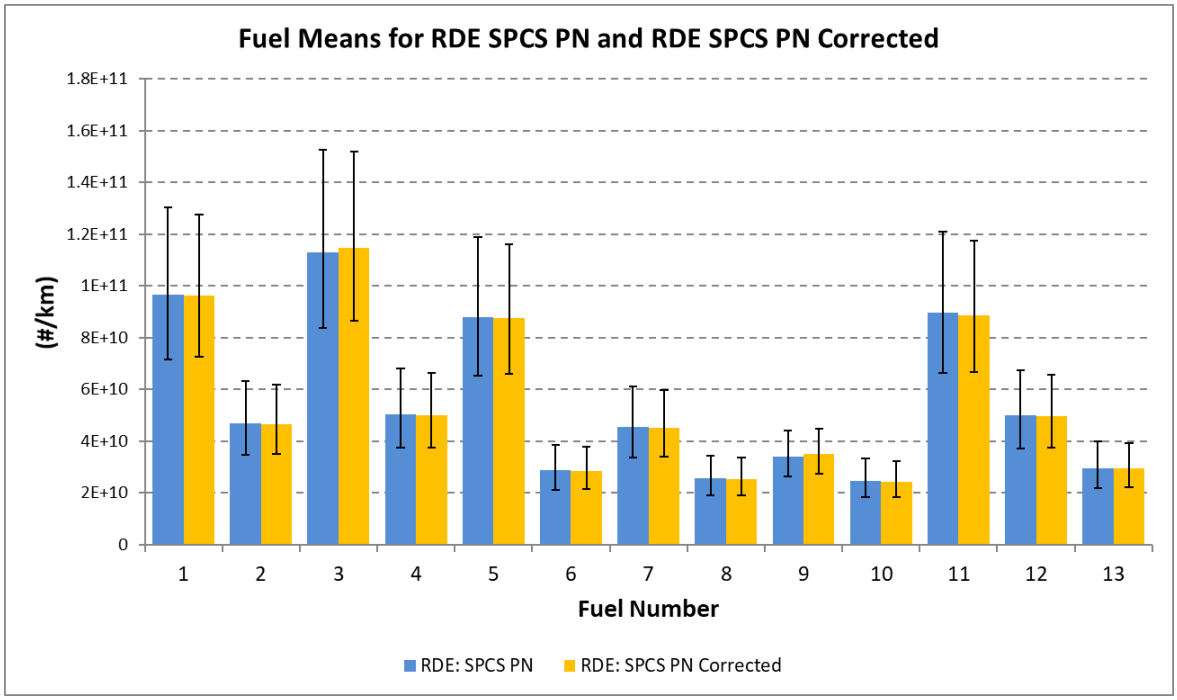


Figure 7.15 Comparison between uncorrected and corrected TP SPCS PN emissions on the RDE cycle.

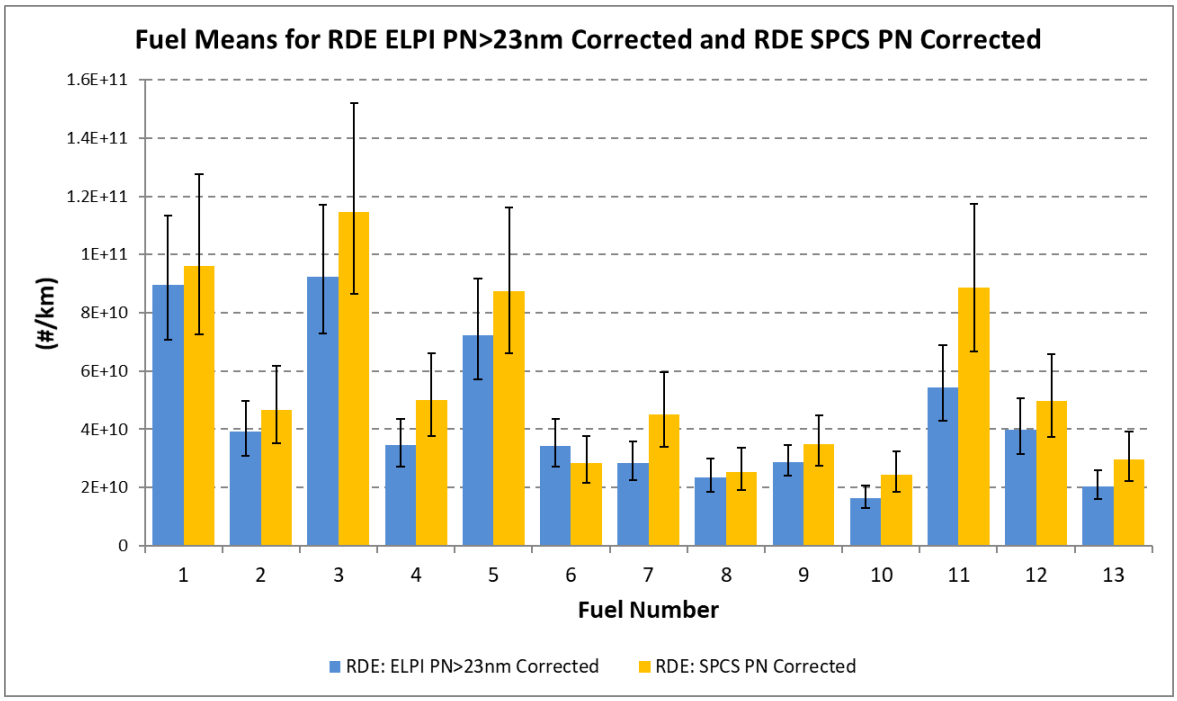


Figure 7.16 Comparison between corrected TP SPCS PN and corrected TP ELPI PN emissions having a diameter bigger than 23 nm on the RDE cycle.

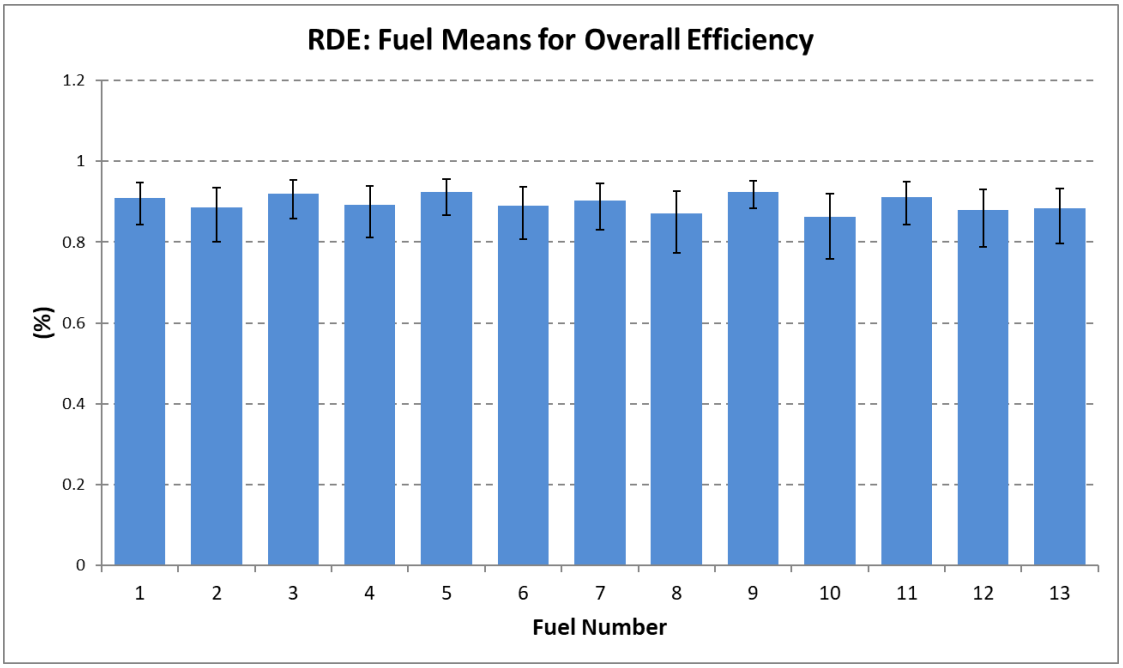


Figure 7.17 Overall GPF filtration efficiency on the RDE cycle.

7.3. SOURCES OF VARIATION

There are two main sources of variation in the data for any measurement: between the fuels (i.e. between the fuel means) and between the repeat tests on the same fuel. This is illustrated in the figure below where the blue circles represent the repeats on the same fuel shown vertically above the corresponding fuel number. The red points are the fuel means.

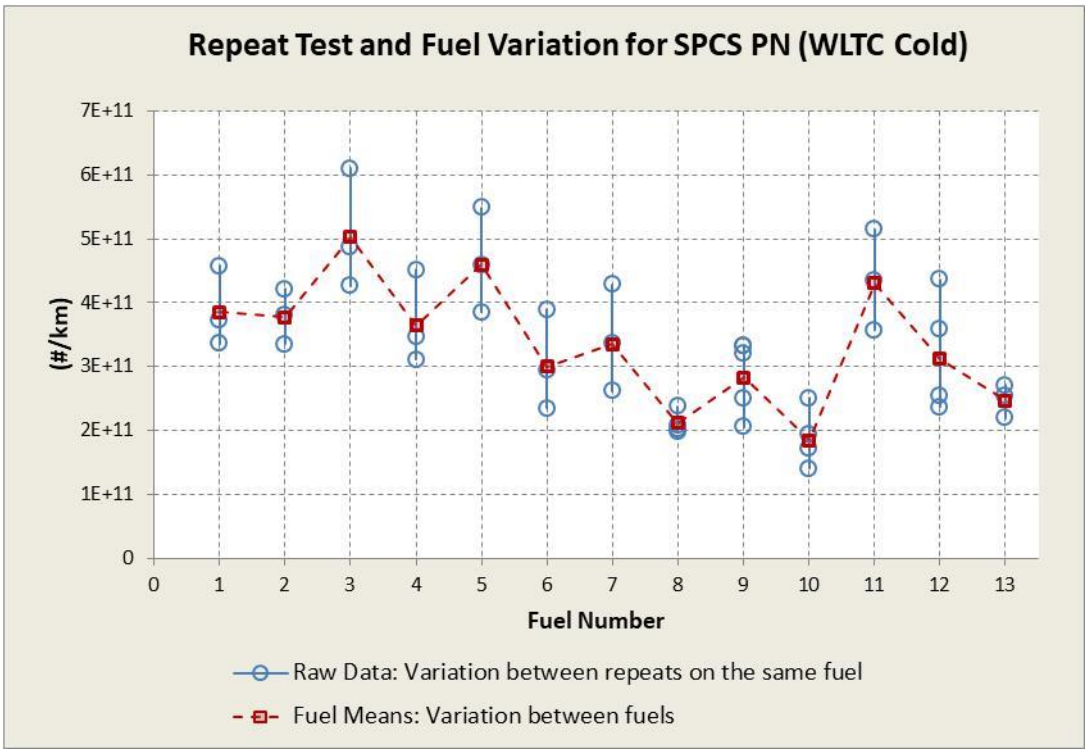


Figure 7.18 Illustration of variation in the SPCS PN (Cold WLTC). Each circle represents a test result with the repeat measurements for each fuel shown vertically above the fuel number. The red points are the fuel means.

Variation between repeat tests on the same fuel is called "Pure error". This source of variation is an inherent feature of the test facility and includes random changes due to environment, driver, vehicle behaviour etc. It may include features such as a trend which can be estimated and removed as has been done with many of the measurements in this study (see above).

Modelling of fuel properties seeks to explain as much as possible of the variation between the fuels. Fuel properties can only explain fuel variation (the variation between the red points in Figure 10). They cannot explain the variation between repeats on the same fuel (blue points for the same fuel) because these measurements all have identical fuel properties.

7.3.1. Lack of fit

The retained fuel properties and the selected models are unlikely to explain 100% of the fuel variation – there will always be some variation remaining that is not accounted for. This remaining variation is known as the lack of fit error. If lack of fit is significantly greater than pure error, then this indicates that there is more to explain and that additional model parameters may be needed to account for the remaining variation.

7.3.2. Significance testing of fuel properties

Fuel properties have been tested for significance against the pure error. Pure error is preferred to the default error term from the model, which is a combination of pure error and lack of fit, for the following reasons:

- Lack of fit may be significantly greater than pure error and it

- Using pure error ensures all fuel properties regardless of the model they are fitted in, are tested against the same, consistent criteria.

- It has a physically meaningful interpretation: a fuel property that is significant compared to pure error can be said to explain significantly more than the inherent random variation in the test process.

Statistical significance of a fuel property implies an association with the response but does not imply causality. There will be other fuel properties not explicitly studied that will vary simultaneously with aromatics, E150 and oxygenates and could be contributing to (or detracting from) the observed effect. There is no statistical way to disentangle the effects of correlated fuel properties.

7.3.3. R^2 and % Fuel variation explained

The R^2 for a model is often cited as a useful measure of goodness of fit even though there is no statistical way to formally compare R^2 from one model to another. In this test programme, the interpretation of R^2 requires additional care.

R^2 is the proportion of the total variation in the data explained by the fitted model.

When a model with Fuel as a factor is fitted to the data, the R^2 value is the proportion of the variation attributable to fuel. 1- R^2 is therefore the proportion of the variation attributable to pure error.

When a model with fuel properties is fitted to the data, the R^2 value is the proportion of the variation accounted for by that model. It is important to note that this cannot be higher than the R^2 obtained from the model with Fuel as a factor. Fuel property models therefore have an upper limit on R^2 which is set by the model which generated the fuel means. This is illustrated in the figure below for Corrected TP SPCS PN emissions. The model with fuel as a factor has R^2 = 0.92 and hence 8% of the variation in the corrected data is attributable to pure error and shown in black on the diagram. The figure shows the R^2 for three fuel property models with R^2 values of 0.80, 0.84 and 0.85 respectively. The red lack of fit is the proportion of the variation in the fuels not accounted for by the fuel property models.

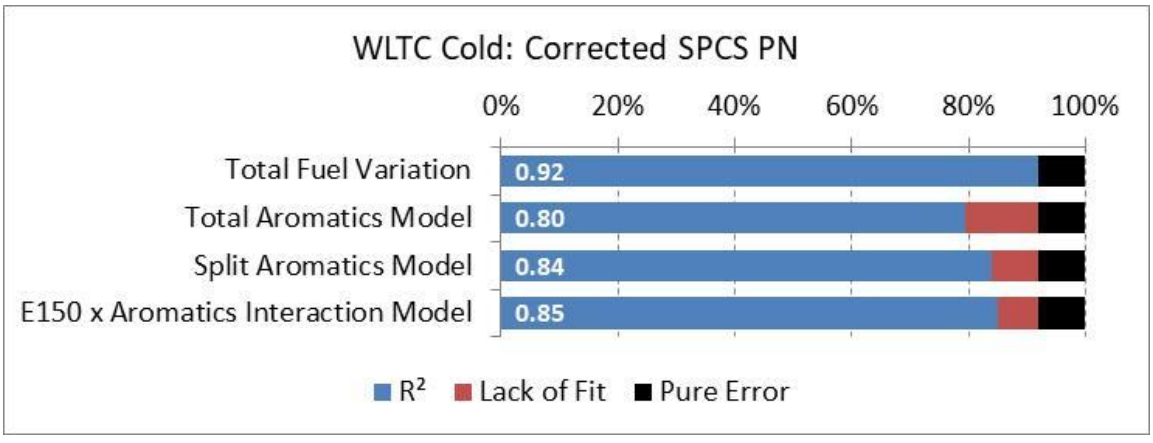


Figure 7.19 Illustration of R^2 for models of Corrected TP SPCS PN emissions.

R^2 for fuel will vary widely from one test cycle to another and from one measurement to another and hence the upper limit on the R^2 for any fuel property model will also vary between test cycles and measurements. The R^2 for fuel property models are therefore not directly comparable from one test cycle to another or from one measurement to another.

An alternative measure for assessing the amount of variation explained is to compute the percentage of the total fuel variation that a model explains by dividing the model R^2 by the R^2 for fuel as shown below for the example of TP SPCS PN emissions. Normalising R^2 by the R^2 for fuel creates a measure that is now comparable across cycles and across measurements.

Table 7.1 Summary of R^2 values for the TP SPCS PN emissions models

Corrected TP SPCS PN emissions Model	%Fuel Variation R^2 Model / R^2 Fuel	R^2	Proportion Lack of Fit R^2 Fuel - R^2 Model	Proportion Pure Error 1-R^2 Fuel
Total Fuel Variation		0.92		0.08
Total Aromatics Model	87%	0.80	0.12	0.08
Split Aromatics Model	92%	0.84	0.08	0.08
E150 x Aromatics Interaction Model	92%	0.85	0.07	0.08

7.4. FUEL PROPERTY MODELLING

7.4.1. Simple Linear Models in the design properties

The primary objective of this test programme was to study the effects of the fuel properties E150, total aromatics and oxygenates with a secondary objective of splitting aromatics into light (<C9) aromatics and heavy (≥C9) aromatics. The main focus of the statistical analysis has been to investigate the effects of these properties as these can be most robustly assessed.

Total aromatics cannot be modelled simultaneously with light and heavy aromatics because total aromatics is the sum of the others (modelling requires independent variables). Two sets of models have therefore been generated: those using total aromatics referred to as the "Total Aromatics Model" and those using light and heavy aromatics referred to as the "Split Aromatics Model":

- Total Aromatics Model: E150 + Total Aromatics + Oxygenates
- Split Aromatics Model: E150 + Light (<C9) Aromatics + Heavy (≥C9) Aromatics + Oxygenates

High oxygenates at three levels of E150 are included in the fuel matrix as a vector on the low aromatics axis only. Blending was extremely consistent and individual fuels deviated only slightly from their intended oxygenate concentrations of 10%v/v or 26.5%v/v. As there are no fuels with intermediate levels of oxygenates, this property has been modelled as a factor "High" corresponding to the 26%v/v level and Low corresponding to the ~10%v/v level.

Modelling has followed a similar approach to that of a previous Concawe study (Report no 2/19 "Effect of Diesel Fuel Properties on Fuel Economy and Emissions of

Three Passenger Cars"). Models have been generated and reported that contain the full set of design properties: E150, Total aromatics & Oxygenates or E150, Light aromatics, Heavy aromatics & Oxygenates, regardless of the statistical significance of the individual properties. This enables the consistency of directional effects, which may not be statistically significant, to be visualised in the results and provides a means of comparing the effects from one cycle or measurement to another.

7.4.2. Interaction Models

In addition to these two main models, interaction models were also considered for E150 at low and high oxygenates and E150 x aromatics.

- E150 x Aromatics + Oxygenates
- E150 x Oxygenates + Aromatics

In contrast to the main models, interaction models are only reported when the interaction is significant at the 95% confidence level ($P<0.05$)

7.4.3. Modelling PM Indices

The correlation between PN emissions measurements and the four PM indices (Honda PM index, E13-E170 PM Index and E150 PM index) was assessed by fitting each individually to see how much of the fuel variation they each can explain. The PM indices are properties of the fuel and hence, like other fuel properties, they cannot explain any of the pure error and are subject to the upper ceiling on R^2 discussed above.

The fuel matrix was designed to deconvolute co-linearity between E150 and aromatics that may occur in real-world fuels and this will limit the performance of the indices. For example, the E150 PM index is perfectly correlated with E150 and so it cannot explain any of the variation in the fuels that was introduced by varying aromatics at constant levels of E150.

All PM indices correlate positively with PN measurements and are compared from cycle to cycle using the percentage of fuel variation they explain as described above.

7.4.4. Modelling additional fuel properties

There was interest in assessing whether any of the following properties correlate with PN emissions (or, in the case of Adiabatic Flame Temperature, with NOX emissions): T90, Final Boiling Point (FBP), Initial Boiling Point (IBP), T10, Vapour Pressure (DVPE) Yield Sooting Index (YSI) and Adiabatic Flame temperature.

These additional properties were all found to be correlated to a greater or lesser extent with at least one of the design properties and there was no evidence that they contributed significantly to the variation once the effects of the design properties were accounted for. The correlations are shown in the following table:

Table 7.2 Matrix of correlations between fuel properties; x-axis are design variables and "y-axis were other properties considered"

T90	-0.9608	0.0043	-0.1164	0.1308	0.1122
FBP	-0.5380	-0.6004	-0.2242	-0.5395	0.3235
IBP	0.1510	-0.5993	-0.5478	-0.1900	0.5011
T10	-0.0187	-0.1667	-0.0274	-0.1872	0.7680
DVPE	-0.0236	0.4219	0.3781	0.1418	-0.5394
YSI	-0.2262	0.9127	0.3933	0.7637	-0.6852
Adiabatic_Flame_Temp	0.3151	0.8299	0.6161	0.4162	-0.4920
	E150	**Aromatics**	**<C9 Aromatics**	**>=C9 Aromatics**	**Oxygenates**

The primary evaluation of these properties was a simple correlation with PN (on the $\log_e$ scale) in a similar way to the evaluation of the PM Indices.

8. PHASE 1 - OUTPUT FROM THE MODELLING

8.1. MODELS

8.1.1. Total Aromatics Model

The Total Aromatics Model for the example of the TP SPCS PN WLTC Cold cycle has the coefficients as shown in the table below:

Table 8.1 Coefficients of the Total Aromatics Model for the TP SPCS PN emissions on the WLTC Cold cycle

	Intercept	Oxygenates	E150	Aromatics
Ln(PN) =	29.522	High	-0.0405	0.0221
	29.395	Low		

It can be read as follows:

- At low (~10%) oxygenates the model is:
    - Ln(PN) = 29.395 – 0.0405 x E150 + 0.0221 x Total Aromatics
- and at high (~26%) oxygenates the model is
    - Ln(PN) = 29.522 – 0.0405 x E150 + 0.0221 x Total Aromatics

The values of aromatics and E150 are their fuel property values on the percent scale i.e. aromatics from 20 to 40 and E150 from 80 to 92. For example, at 27% total aromatics, E150 = 86 & low oxygenates:

- Ln(PN) = 29.395 – 0.0405 x 86 + 0.0221 x 27 = 26.508

and the predicted value of SPCS PN would be: EXP(26.508) = 3.25xE+11

8.1.2. Split Aromatics Model

The Split Aromatics Model for the example of the TP SPCS PN WLTC Cold cycle has the coefficients as shown in the table below:

Table 8.2 Coefficients of the Split Aromatics Model for the TP SPCS PN emissions on the WLTC Cold cycle

	Intercept	Oxygenates	E150	<C9 Aromatics	>=C9 Aromatics
Ln(PN) =	29.934	High	-0.0456	0.0280	0.0110
	29.868	Low			

It can be read as follows:

- At low (~10%) oxygenates the model is:
    - Ln(PN) = 29.868 – 0.0456 x E150 + 0.0280 x Aromatics < C9 + 0.0110 x Aromatics ≥C9
- and at high (~26%) oxygenates the model is

- Ln(PN) = 29.934 – 0.0456 x E150 + 0.0280 x Aromatics < C9 + 0.0110 x Aromatics ≥C9

For example, at 27% total aromatics, E150 = 86 & low oxygenates:

- Ln(PN) = 29.868 – 0.0456 x 86 + 0.0280 x 16 + 0.0110 x 11 = 26.510

and the predicted value of TP SPCS PN emissions would be: EXP(26.510) = 3.26xE+11

8.1.3. E150 x Aromatics Interaction Model

This model considers whether the response to E150 is different at low and high aromatics (and similarly whether the response to aromatics is different at low and high E150). The E150 x Aromatics Interaction Model for the example of the TP SPCS PN WLTC Cold cycle has the coefficients as shown in the table below:

Table 8.3 Coefficients of the E150 x Aromatics Interaction Model for the TP SPCS PN emissions on the WLTC Cold cycle

	Intercept	Oxygenates	E150	Aromatics	E150 x Aromatics
Ln(PN) =	34.482	High	-0.0985	-0.1759	0.00232
	34.361	Low			

A significant interaction is one where the coefficient of E150 (or aromatics) changes significantly as the value of the other property changes. The use of the different intercepts for low and high oxygenates is the same as above. At low oxygenates, the model is

- Ln(PN) = 34.361 – 0.0985 x E150 - 0.1759 x Total Aromatics + 0.00232 x E150 x Total Aromatics

For example, at 27% total aromatics, E150 = 86 & low oxygenates:

- Ln(PN) = 34.361 – 0.0985 x 86 - 0.1759 x 27 + 0.00232 x 86 x 27= 26.519

and the predicted value of TP SPCS PN emissions would be: EXP(26.519) = 3.29xE+11

8.1.4. E150 x Oxygenates Interaction Model

This model considers whether the response to E150 is different at low and high oxygenates. The E150 x Oxygenates Interaction Model for the example of the TP SPCS PN WLTC Cold cycle has the coefficients as shown in the table below:

Table 8.4 Coefficients of the E150 x Oxygenates Interaction Model for the TP SPCS PN emissions on the WLTC Cold cycle

	Intercept	Oxygenates	E150	Aromatics
Ln(PN) =	37.455	High	-0.1370	0.0679
	30.260	Low	-0.0602	

A significant interaction is one where the coefficient of E150 is significantly different at low aromatics to what it is as might oxygenates. In this model, the coefficient of E150 takes a different value depending on whether oxygenates are low (~10%) or high (~26%).

- At low oxygenates, the model is
    - Ln(PN) = 30.260 – 0.0602 x E150 + 0.0679 x Total Aromatics
- and at high oxygenates the model is
- Ln(PN) = 37.455 – 0.1370 x E150 + 0.0679 x Total Aromatics

For example, at 27% total aromatics, E150 = 86 & low oxygenates:

- Ln(PN) = 30.260 – 0.0602 x 86 + 0.0679 x 27 = 26.915

and the predicted value of TP SPCS PN emissions would be: EXP(26.915) = 4.89xE+11

8.2. SIGNIFICANCE LEVELS OF FUEL PROPERTIES

The significance level of fuel properties is indicated throughout the results using the following key:

Table 8.5 Key to significance of the fuel properties in the models

Key to Significance	
Sig @ 99.9% P< 0.001	***
Sig @ 99% P< 0.01	**
Sig @ 95% P<0.05	*
Sig @ 90% P<0.1	o

9. PHASE 1 - MODELLING RESULTS

A big number of models was created throughout the modelling work. To avoid showing an extensive list of graphs and tables, the focus is made on the main outcomes of the study: TP SPCS PN emissions, EO ELPI PN emissions and overall GPF filtration efficiency. Each of them is shown on the cold WLTC and the hot WLTC to get insights about the effect of temperature.

9.1. TAILPIPE SPCS PN EMISSIONS

The modelling is based on the trend-corrected data, as described above.

The table below shows that E150 and total aromatics are the most significant fuel parameters in the total aromatics model on the cold WLTC; in the split aromatics model, light aromatics (< C9 aromatics) are also a significant parameter, and E150*aromatics is a significant interaction in the corresponding model. The modelling on the cold WLTC finds out that oxygenates content and heavy aromatics (> C9 aromatics) are less significant parameters. On the hot WLTC, all these parameters are found significant, except the E150*aromatics interaction.

Table 9.1 Significance of fuel parameters on the TP SPCS PN emissions models. In red: increasing the fuel property results in increasing TP SPCS PN emissions; in green: increasing the fuel property results in decreasing TP SPCS PN emissions

Significance of Effect		
Fuel Properties	**WLTC Cold Cycle**	**WLTC Hot Cycle**
Oxygenates	**	***
E150	***	***
Aromatics	***	***
<C9 Aroms	***	***
>=C9 Aroms	**	***
*E150*Aromatics*	***	

The table below provides the magnitude of fuel parameters effects on the TP SPCS PN emissions. Before going any further, it is important to give a disclaimer about these results: no matter how tempting it can be, no conclusion can be drawn from the impact of a single, isolated parameter on the PN emissions. The reason for this is that the mathematical model ignores that the fuel parameters are interrelated and cannot be varied alone. For example, it would be tempting to conclude from the table below that, on the cold WLTC, increasing the heavy aromatics (> C9 aromatics) from 5% to 25% increases the PN emissions less (25% vs 75%) than increasing the light aromatics (< C9 aromatics) from 5% to 25%. But such a conclusion would ignore that the E150 would likely decrease in parallel of increasing heavy aromatics, resulting in an additional increase of PN emissions according to the model. Therefore, even if the models of TP SPCS PN emissions are fairly good (see further below), they must be understood as a whole (i.e. encompassing all the fuel properties of a real fuel) without isolating the impact of a single parameter.

Table 9.2 Magnitude of fuel parameters effects on the TP SPCS PN emissions. Key to reading the table: increasing E150 from 80% to 92% results in decreasing TP SPCS PN emissions by 39% on the cold WLTC.

Magnitude of Effect		
Fuel Properties	**WLTC Cold Cycle**	**WLTC Hot Cycle**
Oxygenates from Low (10%) to High (26%)	**13%**	**75%**
E150 from 80% to 92%	**-39%**	**-55%**
Aromatics from 20% to 40%	**56%**	**271%**
<C9 Aroms from 5% to 25%	**75%**	**255%**
>=C9 Aroms from 5% to 25%	**25%**	**304%**
Aromatics from 20% to 40% at Low E150	***21%***	
Aromatics from 20% to 40% at High E150	***110%***	
E150 from 80% to 92% at Low Aromatics	***-47%***	
E150 from 80% to 92% at High Aromatics	***-7%***	

After correction of the trends, the pure error remaining on the TP SPCS PN emissions of the cold and hot WLTC is rather small (around 10%), which provides robust data for modelling purpose. In this context, it was possible to obtain fairly good models, with R^2 ranging between 0.80 and 0.86. It is remarkable that providing more information about fuel parameters to the model (from total aromatics model to split aromatics and E150*aromatics models) results in a limited improvement of the model quality. In fact, a simple linear model such as the total aromatics model, having only two parameters (E150 and total aromatics, and 2 levels of oxygenates), already provides a good correlation between the measurements and the modelling results. It is also remarkable that the PM indices (Honda PM index, E130-E170 PM index and E150 PM index) correlate very poorly with the measurements, showing the incapability of these models to actually predict PN emissions from a vehicle on which they were not calibrated.

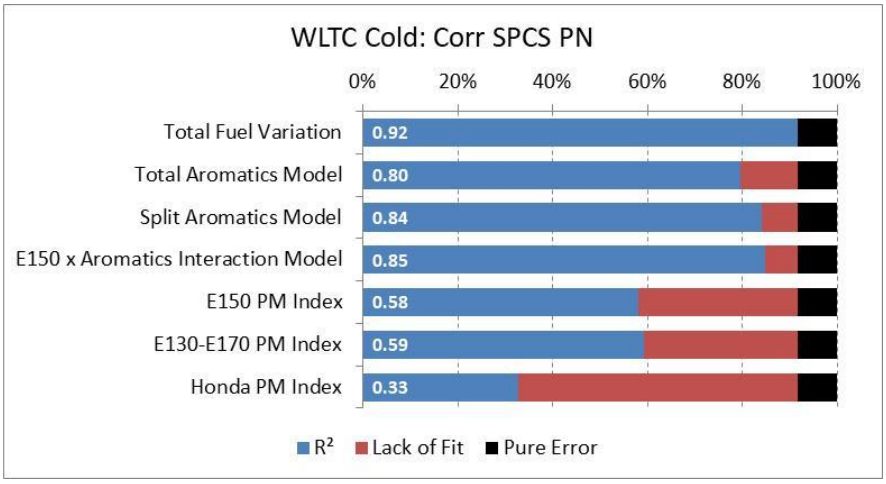


Figure 9.1 R^2, lack of fit and pure error of the TP SPCS PN emissions models on the cold WLTC

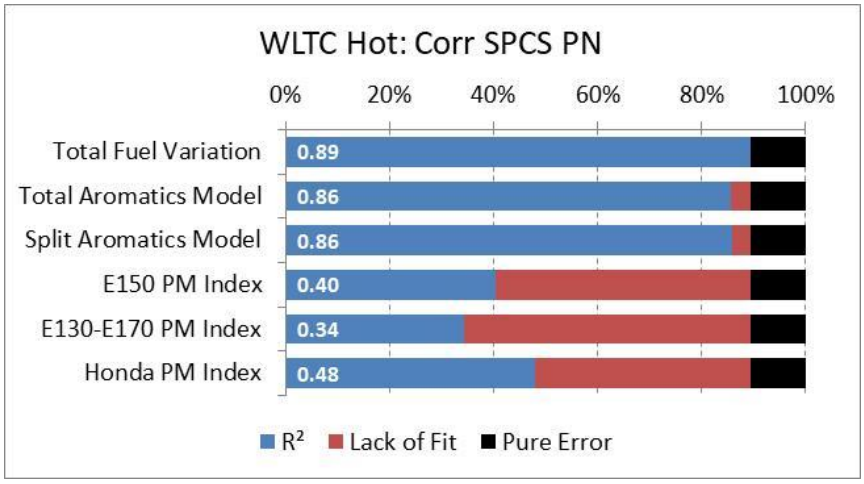
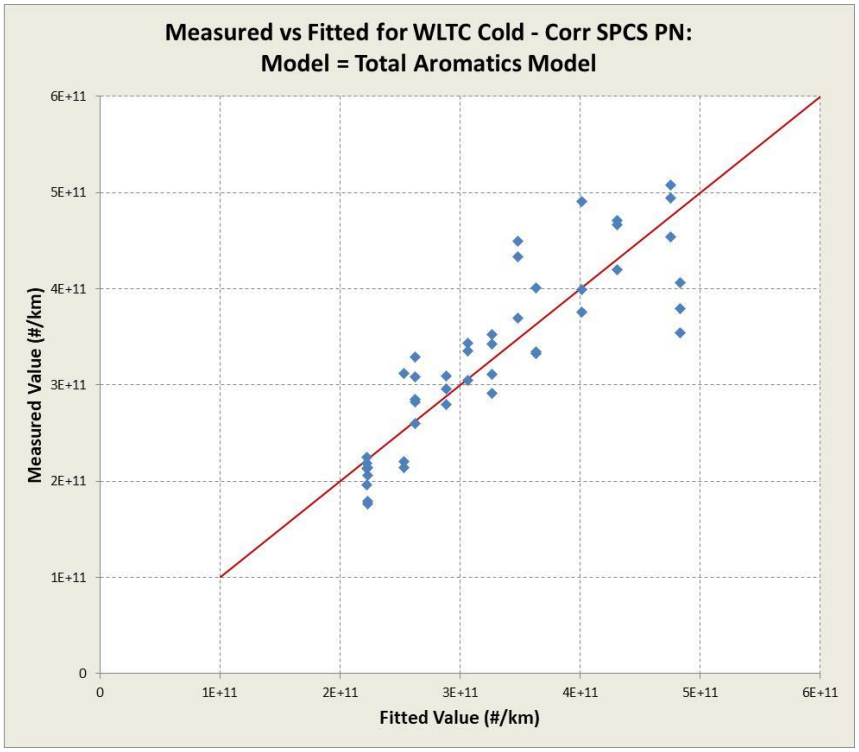


Figure 9.2 R^2, lack of fit and pure error of the TP SPCS PN emissions models on the hot WLTC

The figures below provide the parity plots between individual TP SPCS PN emissions measurements and models for the cold and hot WLTC. Each row of the x-axis is one of the 13 fuels, while the y-axis has 6 PN measurements. It can be observed that the dots are relatively close to the parity line, meaning that there is a good fit between the mathematical model and the measurements.



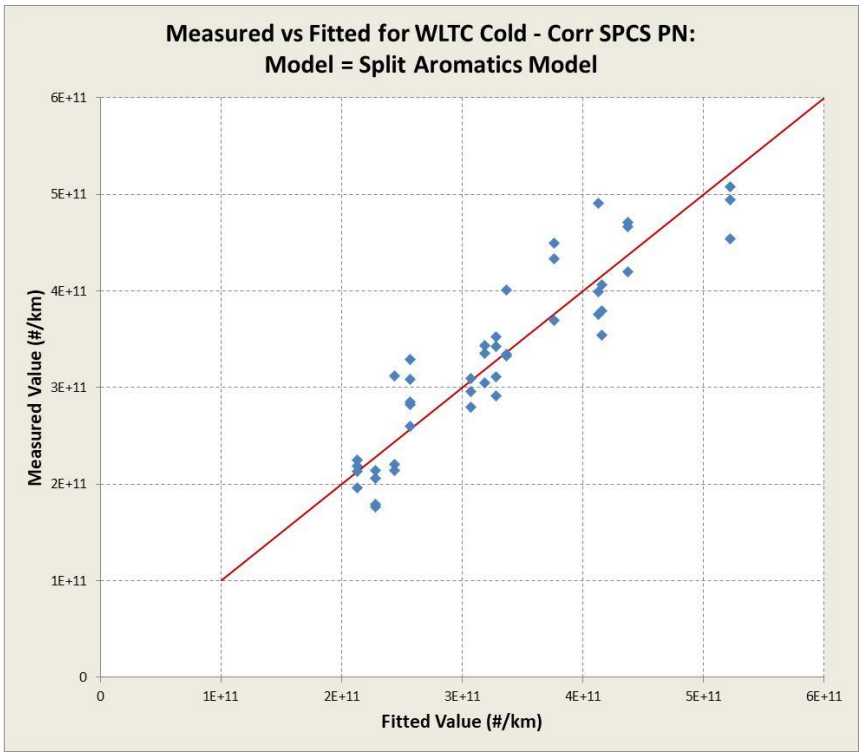
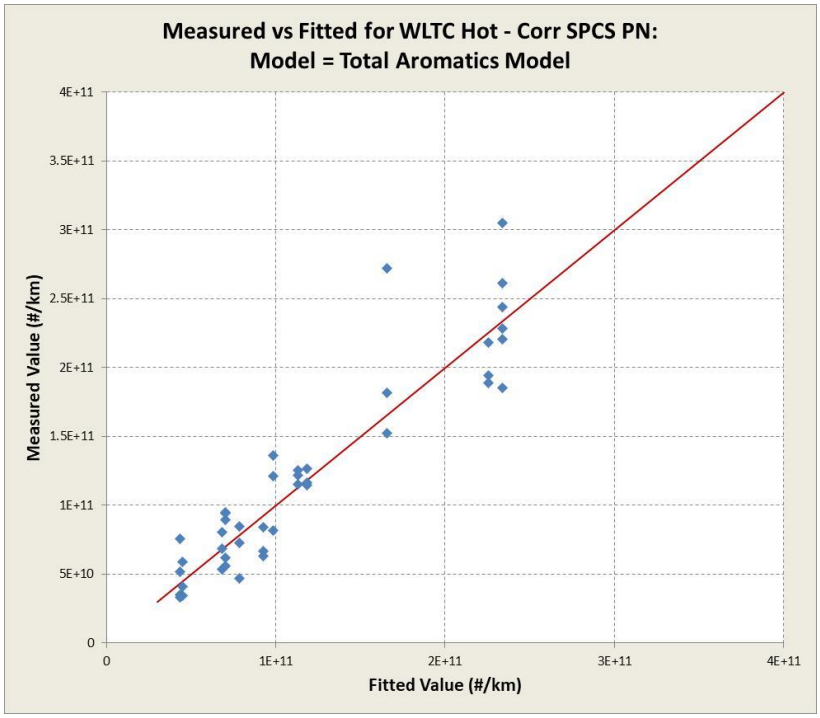


Figure 9.3 Parity plots: measured vs modelled TP SPCS PN emissions on the cold WLTC for the total aromatics model and the split aromatics model.



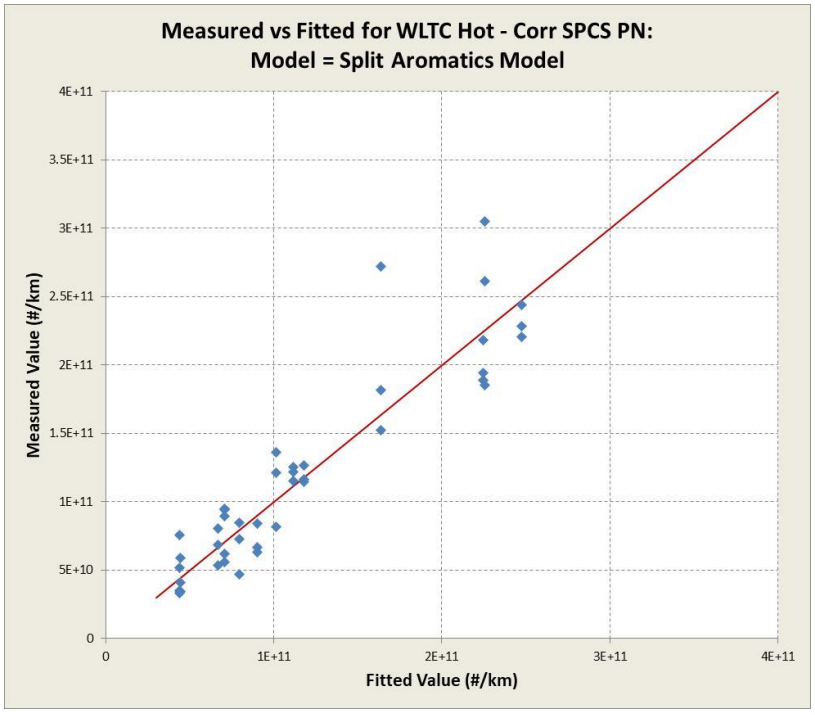


Figure 9.4 Parity plots: measured vs modelled TP SPCS PN emissions on the hot WLTC for the total aromatics model and the split aromatics model.

The figures below show the parity plots between mean TP SPCS PN emissions measurements and each of the evaluated PM indices (Honda PM index, E130-E170 PM index and E150 PM index) and provide another angle about the poor correlations between these PM indices and the PN emissions measurements.

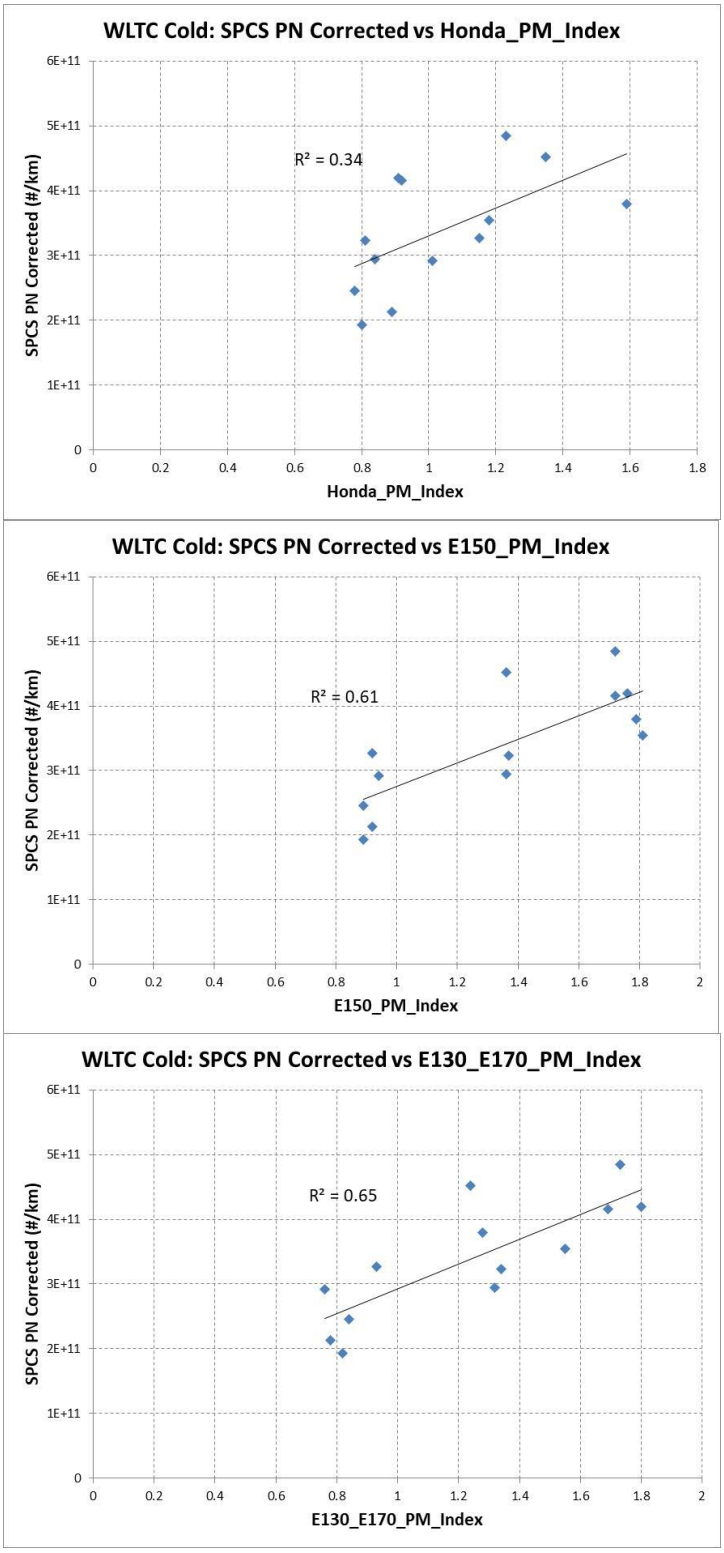


Figure 9.5 Parity plots: measured TP SPCS PN emissions on the cold WLTC vs PM indices. Top: Honda PM index; Middle: E150 PM index; Bottom: E130-E170 PM index

The figure below shows the parity plots between mean TP SPCS PN emissions measurements and the Yield Sooting Index and demonstrates that this indicator is not fit for predicting the TP PN emissions of this vehicle.

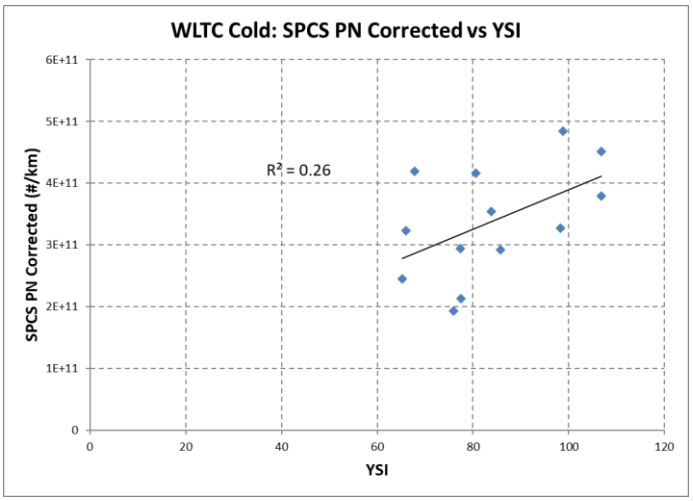


Figure 9.6 Parity plot: measured TP SPCS PN emissions on the cold WLTC vs Yield sooting index (YSI)

9.2. ENGINE-OUT ELPI PN EMISSIONS

The modelling is based on uncorrected data.

The table below shows that E150 and total aromatics are the most significant fuel parameters in the total aromatics model on the cold WLTC; in the split aromatics model, light aromatics (< C9 aromatics) are also a significant parameter. The modelling on the cold WLTC finds out that oxygenates content is not a significant parameter, and heavy aromatics (> C9 aromatics) and E150*aromatics interaction in the corresponding models are less significant parameters. On the hot WLTC, all these parameters are found significant, except the E150*aromatics interaction.

Table 9.3 Significance of fuel parameters on the EO ELPI PN emissions models. In red: increasing the fuel property results in increasing EO ELPI PN emissions; in green: increasing the fuel property results in decreasing EO ELPI PN emissions

Significance of Effect		
Fuel Properties	**WLTC Cold Cycle**	**WLTC Hot Cycle**
Oxygenates	Not Sig	***
E150	***	***
Aromatics	***	***
<C9 Aroms	***	***
>=C9 Aroms	*	***
*E150*Aromatics*	*	
*E150*Oxygenates*		*

The table below provides the magnitude of fuel parameters effects on the EO ELPI PN emissions. The important disclaimer about these results is reminded here: no

conclusion can be drawn from the impact of a single, isolated parameter on the PN emissions because the mathematical model ignores that the fuel parameters are interrelated and cannot be varied alone. For example, it would be tempting to conclude from the table below that, on the cold WLTC, increasing the heavy aromatics (> C9 aromatics) from 5% to 25% increases the PN emissions less (51% vs 154%) than increasing the light aromatics (< C9 aromatics) from 5% to 25%. But such a conclusion would ignore that the E150 would likely decrease in parallel of increasing heavy aromatics, resulting in an additional increase of PN emissions according to the model. Therefore, even if the models of EO ELPI PN emissions are acceptable (see further below), they must be understood as a whole (i.e. encompassing all the fuel properties of a real fuel) without isolating the impact of a single parameter.

Table 9.4 Magnitude of fuel parameters effects on the EO ELPI PN emissions. Not mentioned in the table: Oxygenates vary from low (10%) to high (26%); E150 varies from 80% to 92%; Aromatics vary from 20% to 40%; < C9 aromatics vary from 5% to 25%; >= C9 aromatics vary from 5 to 25%. Key to reading the table: increasing E150 from 80% to 92% results in decreasing EO ELPI PN emissions by 47% on the cold WLTC.

Magnitude of Effect		
Fuel Properties	**WLTC Cold Cycle**	**WLTC Hot Cycle**
Oxygenates	7%	**77%**
E150	**-47%**	**-60%**
Aromatics	**112%**	**277%**
<C9 Aroms	**154%**	**283%**
>=C9 Aroms	**51%**	**266%**
Aromatics from 20% to 40% at Low E150	***50%***	
Aromatics from 20% to 40% at High E150	***217%***	
E150 from 80% to 92% at Low Aromatics	***-56%***	
E150 from 80% to 92% at High Aromatics	***-7%***	
E150 from 80% to 92% at Low Oxygenates		***-51%***
E150 from 80% to 92% at High Oxygenates		***-81%***

After correction of the trends, the pure error remaining on the EO ELPI PN emissions of the cold and hot WLTC is rather limited (around 20%), which provides robust data for modelling purpose. In this context, it was possible to obtain models of mild quality, with R^2 ranging between 0.66 and 0.77. It is remarkable that providing more information about fuel parameters to the model (from total aromatics model to split aromatics and E150*aromatics models) results in a limited improvement of the model quality. In fact, a simple linear model such as the total aromatics model, having only two parameters (E150 and total aromatics, and 2 levels of oxygenates), already provides a mild correlation between the measurements and the modelling results. It is also remarkable that the PM indices (Honda PM index, E130-E170 PM index and E150 PM index) correlate very poorly with the measurements, showing the incapability of these models to actually predict PN emissions from a vehicle on which they were not calibrated.

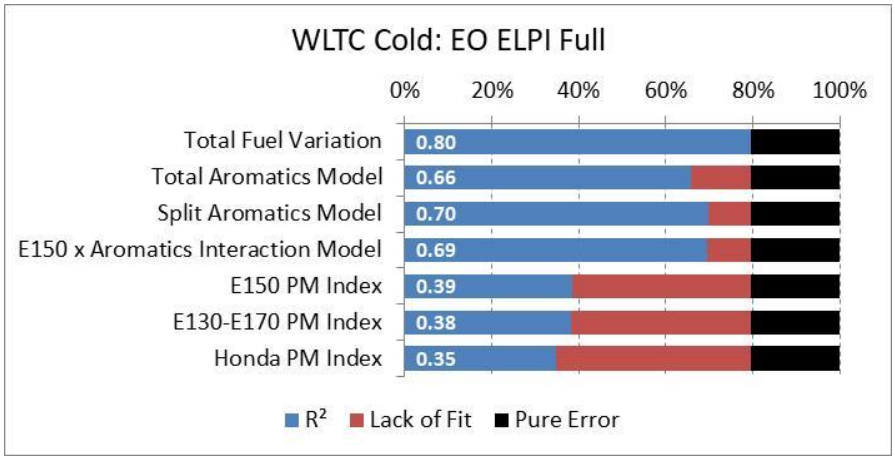


Figure 9.7 R^2, lack of fit and pure error of the EO ELPI PN emissions models on the cold WLTC

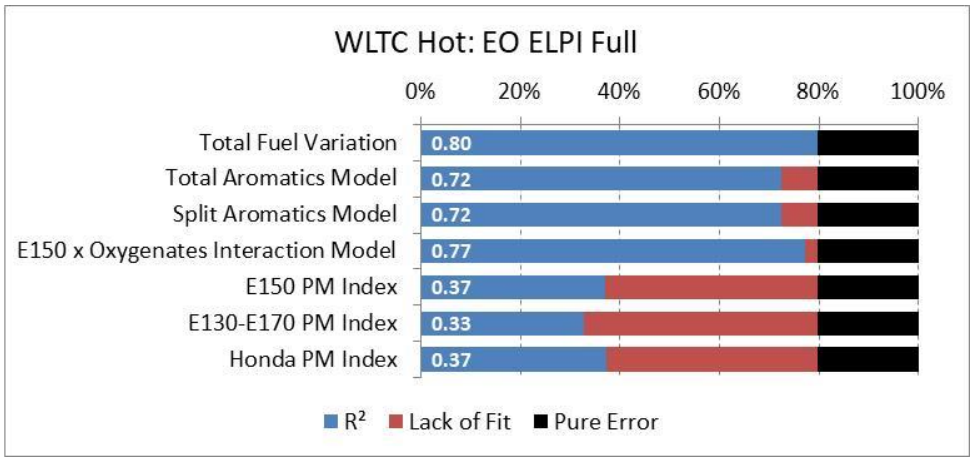


Figure 9.8 R^2, lack of fit and pure error of the EO ELPI PN emissions models on the hot WLTC

The figure below shows the parity plots between mean EO ELPI PN emissions measurements and the Yield Sooting Index and demonstrates that this indicator is not fit for predicting the EO PN emissions of this vehicle.

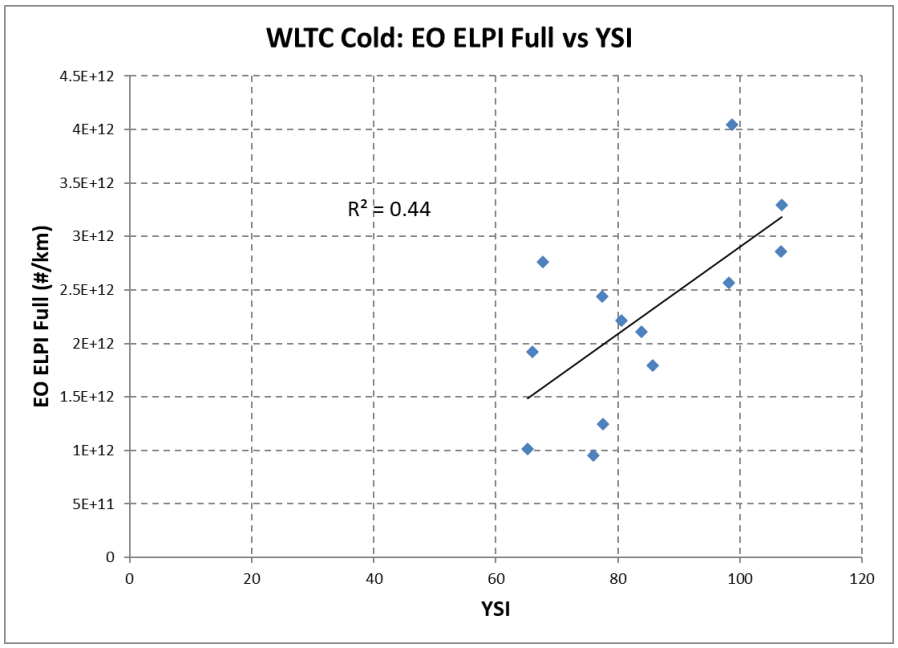


Figure 9.9 Parity plot: measured EO ELPI PN emissions on the cold WLTC vs Yield sooting index (YSI)

9.3. OVERALL GPF FILTRATION EFFICIENCY

The modelling is based on uncorrected data.

The table below shows that almost no fuel parameter is significant to the overall GPF filtration efficiency model. There could be two different reasons for this:

- The first reason might be physical: it may be that fuel is not a relevant parameter to GPF filtration efficiency variation, and therefore it is not possible to make a GPF filtration efficiency model from the fuel properties.

- The second reason might be statistical: if the collected data is too noisy, and if this noise is greater than any fuel impact, then it becomes impossible to observe any fuel-related effect.

Table 9.5 Significance of fuel parameters on the overall GPF filtration efficiency models. In red: increasing the fuel property results in increasing overall GPF filtration efficiency; in green: increasing the fuel property results in decreasing overall GPF filtration efficiency

Significance of Effect		
Fuel Properties	**WLTC Cold Cycle**	**WLTC Hot Cycle**
Oxygenates	Not Sig	Not Sig
E150	o	Not Sig
Aromatics	**	Not Sig
<C9 Aroms	**	Not Sig
>=C9 Aroms	Not Sig	Not Sig

The table below provides the magnitude of fuel parameters effects on the overall GPF filtration efficiency. What can be observed is in line with the statement made above: the fuel parameters do not have any significant effect on the variation of the GPF filtration efficiency.

Table 9.6 Magnitude of fuel parameters effects on the overall GPF filtration efficiency. Key to reading the table: increasing Aromatics from 20% to 40% results in increasing overall GPF filtration efficiency by 10.9% on the cold WLTC. The values in grey (not in bold style) are related to non-significant parameters.

Magnitude of Effect		
Fuel Properties	**WLTC Cold Cycle**	**WLTC Hot Cycle**
Oxygenates from Low (10%) to High (26%)	-1.8%	0.6%
E150 from 80% to 92%	-6.1%	-2.8%
Aromatics from 20% to 40%	**10.9%**	4.1%
<C9 Aroms from 5% to 25%	**13.5%**	6.5%
>=C9 Aroms from 5% to 25%	7.4%	-0.2%

The two figures below show that the pure error in the GPF filtration efficiency is big (between 60% and 85%). Under these conditions, it is understandable that it is difficult to establish any fuel-related model.

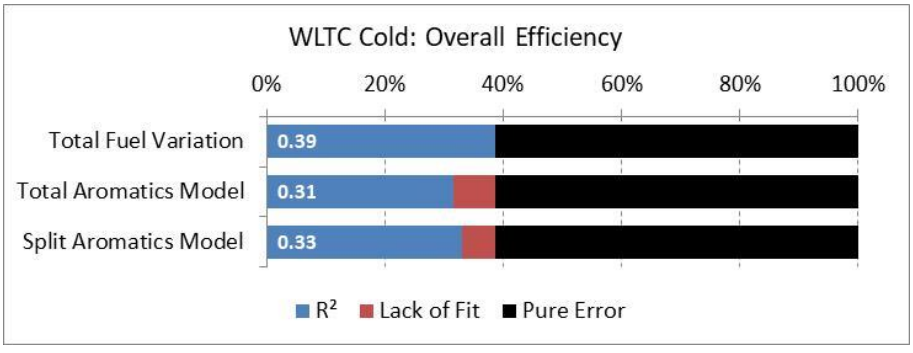


Figure 9.10 R^2, lack of fit and pure error of the overall GPF filtration efficiency models on the cold WLTC

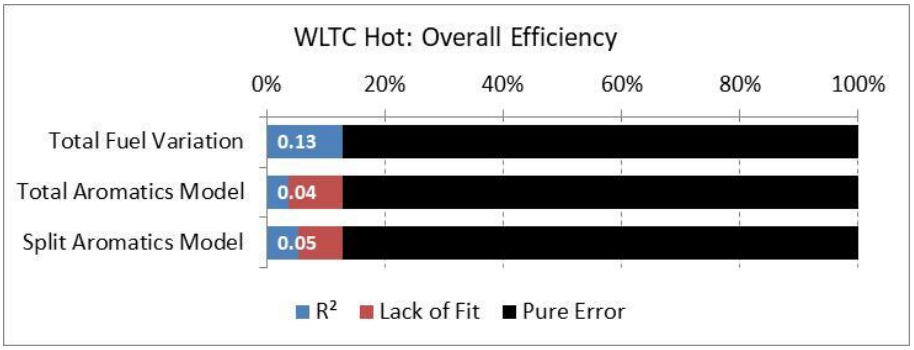


Figure 9.11 R^2, lack of fit and pure error of the overall GPF filtration efficiency models on the hot WLTC

9.4. GASEOUS EMISSIONS

The modelling is based on the trend-corrected data.

The conversion of emissions from engine-out to tailpipe, achieved by the three-way catalyst, and averaged over the 13 fuels, is tabulated below:

Table 9.7 Average conversion of emissions from engine-out to tailpipe, achieved by the three-way catalyst

	CO	HC	NOX
WLTC Cold full cycle	95.2%	97.5%	99.0%
WLTC Cold Phase 1	88.8%	91.1%	87.3%
WLTC Hot full cycle	97.1%	99.9%	99.5%
RDE full cycle	95.9%	98.6%	99.7%

With such high conversion rates, it is difficult to consider that any fuel effect can be observed at the tailpipe. The tables below confirm that fuel parameters are not significant to the tailpipe CO, HC and NOx emissions, with the exception of oxygenates and E150 being sometimes significant to tailpipe CO emissions. Consequently, it was not possible to fit any fuel-related model to the tailpipe gaseous emissions.

Table 9.8 Significance of fuel parameters on the tailpipe CO emissions models. In red: increasing the fuel property results in increasing tailpipe CO emissions; in green: increasing the fuel property results in decreasing tailpipe CO emissions

Tail Pipe CO	WLTC Cold	WLTC Cold Phase 1	WLTC Hot	RDE
Fuel Properties				
Oxygenates	***	***	Not Sig	**
E150	***	***	*	*
Aromatics	Not Sig	*	***	*
<C9 Aroms	Not Sig	o	***	o
>=C9 Aroms	Not Sig	Not Sig	Not Sig	*
*E150*Oxygenates*			**	

Table 9.9 Significance of fuel parameters on the tailpipe HC emissions models. In red: increasing the fuel property results in increasing tailpipe HC emissions; in green: increasing the fuel property results in decreasing tailpipe HC emissions

Tail Pipe HC	WLTC Cold	WLTC Cold Phase 1	WLTC Hot	RDE
Fuel Properties				
Oxygenates	**	**	Not Sig	Not Sig
E150	Not Sig	Not Sig	Not Sig	Not Sig
Aromatics	Not Sig	Not Sig	Not Sig	*
<C9 Aroms	Not Sig	Not Sig	Not Sig	**
>=C9 Aroms	Not Sig	Not Sig	Not Sig	Not Sig

Table 9.10 Significance of fuel parameters on the tailpipe NOx emissions models. In red: increasing the fuel property results in increasing tailpipe NOx emissions; in green: increasing the fuel property results in decreasing tailpipe NOx emissions

Tail Pipe NOX	WLTC Cold	WLTC Cold Phase 1	WLTC Hot	RDE
Fuel Properties				
Oxygenates	*	***	Not Sig	Not Sig
E150	o	Not Sig	Not Sig	o
Aromatics	Not Sig	Not Sig	*	Not Sig
<C9 Aroms	Not Sig	Not Sig	*	Not Sig
>=C9 Aroms	Not Sig	Not Sig	Not Sig	o
*E150*Aromatics*			**	

10. PHASE 1 - CONCLUSIONS

During the first phase of this programme, 13 formulated fuels (surrogates) were tested on a single vehicle equipped with a gasoline direct injection (GDI) engine and a gasoline particulate filter (GPF). The fuel matrix was designed to intentionally and independently vary different fuel properties suspected to impact PN emissions (according to the literature): volume evaporated at 150°C (E150) as a proxy of the heavy fraction of gasoline, total aromatics content, heavy aromatics content (more than 9 carbons) and ethanol content. The vehicle was tested using an "ambient start" (23°C) WLTC (Worldwide harmonized Light vehicle Test Cycle), a "hot start" WLTC and a test cycle simulating RDE (Real Driving Emissions) conditions. During the laboratory tests, both gaseous and particulate engine-out (EO) and tailpipe (TP) emissions were sampled. The particulate sampling included continuous PN10 and PN23 (PN having a diameter respectively bigger than 10 nm and 23 nm). In this first phase, it was concluded that it was possible to establish a fairly good and simple model between TP PN emissions and the fuel properties targeted in the fuel matrix, and more particularly E150 and total aromatics content. The experimental data was also used to check the correlation to other PN models referenced in the literature: "Honda PM index", "Yield Sooting Index" (YSI), simplified PM index (based on E130 and E170) or simple correlation with E150. It was found that none of these models correlate with the experimental data collected, showing the incapability of these literature models to actually predict PN emissions from the test vehicle on which they were not calibrated.

SECTION 3

TRANSITION FROM PHASE 1 TO PHASE 2

11. TRANSITION FROM PHASE 1 TO PHASE 2

The results collected during the first phase of the study demonstrate that, on one hand, it was easy to establish a simple model based on only two simple parameters such as E150 and total aromatics content; and on the other hand, it was impossible to find any correlation with any other existing PN models, including more complex ones. This conflict raised two fundamental questions on what was done during the first phase of the study:

- Would the models developed on the tested vehicle be valid on other vehicles?

- Would the models developed on the tested fuel matrix composed of surrogates be also valid on a fuel matrix composed of real market fuels?

These questions triggered the second phase of this study. This time, the study will be conducted on three vehicles. Two of the studied vehicles will be equipped with GDI technology (vehicles A and B), while the third one (vehicle C) will be equipped with a port fuel injection (PFI) engine. All of them will be equipped with GPFs. Eight market fuels, sampled from European refineries will be tested on each of the vehicles. The fuel matrix will be designed to vary different fuel properties such as E150, total aromatics and olefins content or ethanol content by targeting specific samples in the refineries, but without any specific intervention in the fuel design. Additionally, two fuels will be specifically formulated to complete the fuel matrix, reaching a total of ten fuels. The range of variation of the fuel properties will be selected to match the values seen in the EU FQD market survey. This second phase will follow a similar structure as the first one: an experimental part for the purpose of vehicles testing, with an experimental setup similar to the first phase (using a different RDE cycle and with a cold start at 12°C to be representative of average real-world conditions in Europe); and a modelling part, focused mainly on relationships between fuel properties and PN emissions with a specific part on vehicles cross-comparisons regarding their fuel response.

SECTION 4

GASOLINE PARTICULATE STUDY – PHASE 2

12. PHASE 2 - INTRODUCTION

In 2019 - 2020, Concawe coordinated a study on gasoline particulate emissions. The purpose of the work was to improve the understanding of particulate emissions behaviour for gasoline powered cars in relation to fuel characteristics. The study included 13 test fuels in total with different fuel characteristics. The fuels were tested with one vehicle in WLTC cold, WLTC hot and in an RDE simulated tests. The key results indicated that there are certain fuel characteristics that correlated relatively well with the PN characteristics, e.g. E150 and fuel aromatics content. The outcome of the project was a PN model, which could be used for predicting the change in particulate emissions in respect of change in E150 and aromatics content. The model only included fitted data of one vehicle, thus no decisive conclusions could be drawn that could directly be applied as a general model.

In 2022, Concawe coordinated a continuation of the previous study. The purpose of this study was to further extend the scope to market ready fuels using several different types of vehicles. The vehicles were selected to represent typical gasoline vehicle technologies currently on the market. This report describes the content and key findings of this study.

13. PHASE 2 - PROJECT PROGRAM AND DESRIPTION OF PROJECT OBJECTIVES

The main goal of this study was to produce extensive particulate emission data (experimentally) from gasoline vehicles related to particulate emissions. This data would then be used for studying the potential of generating a PN model for modelling and predicting the influence of changes in fuel properties in relation to behaviour of gasoline particulate emissions. Furthermore, an analysis of the PN model generated in the previous Concawe study would be compared and evaluated against the obtained emission results. The experimental study was performed on a chassis dynamometer simulating typical RDE conditions with an ambient temperature of 12 °C. The experimental part was conducted at the vehicle laboratory at VTT (Technical research centre of Finland), located in Espoo, Finland. The main tasks of the project were divided into three parts as described below:

a. Part 1: Fuel procurement (Coordinated by Concawe and its members)
b. Concawe members to share fuel survey data to identify the boundaries of EU gasoline targeted properties.
c. Concawe members to share the certificate of analysis of gasoline at their refinery terminals, which can potentially be shipped in sufficient quantities (e.g. 200 L) to the test provider.
d. Concawe secretariat to anonymize the fuel data shared by the members.
e. Concawe members to procure and ship the fuels for the fuel matrix to the test provider.

f. Part 2: Statistical support
g. Part 2-a: Test matrix design (Coordinated by Concawe and its members)
h. Based on the data from the fuel survey and from the certificate of analysis, select at least 10 fuels to design the fuel matrix, which must:
i. Be representative of the properties of EU market gasoline
j. Include 1 or 2 fuels from the previous study
k. Include at least one E20, obtained by splash blending and/or fuel formulation
l. Include fitting and validation points
m. Design the test order considering the fuels and the vehicles. Specific considerations were made regarding the possibility of identifying potential deviations during the test campaign and assessing the interval of confidence of the obtained results.

n. Part 2-b: PN emissions modelling (Conducted by VTT)
o. Data analysis was done with a view to identify and potentially eliminate outliers and advise on tests to be rerun. In case of abnormal increasing or decreasing trend would be identified, the data was corrected to avoid any bias on the models
p. PN emissions modelling based on fuel properties
q. Comparison of the models obtained for each vehicle
r. Comparison with the model obtained in the previous study. Comparison with the other existing models.
s. Conclusions on the possibility/impossibility to obtain a “universal” PN emissions model based on fuel properties.

t. Part 3: Vehicle tests on a chassis dyno (Conducted at VTT)
u. Procurement of 3 vehicles to be discussed with Concawe and its members.
v. Break-in of the vehicles if their mileage is lower than 3000 km
w. Chassis dyno-tests according to the test matrix:
    - 90 tests on a chassis dynamometer simulating RDE conditions.

- For repeatability reasons, back-to-back tests was avoided. Therefore, fuel was switched between each test on each vehicle.
- RDE-compliant cycle (provided by VTT), agreed with project partners
- The tests were conducted as cold start with and ambient temperature at 12°C.
- The lubricant level was monitored in the oil sump, and a top-up/oil drain will be done only in case of oil consumption/dilution (not likely to happen at first sight). In case a problem is detected, a sample of the lubricant will be taken.

14. PHASE 2 - METHODOLOGY OF THE EXPERIMENTAL STUDY

This chapter describes the complete methodological process of the experimental study. Since the aim of the study was to extend the understanding of the particulate emission formation behaviour of gasoline vehicles in on-road driving conditions, but simultaneously being able to perform a complex experimental study with both engine out (EO) and tail-pipe (TP) emission measurements, the experimental part was performed on a chassis dyno environment using simulated on-road driving conditions. The experimental study was performed at the VTT Technical Research Centre of Finland vehicle laboratory in Otaniemi (Espoo), Finland.

14.1. TEST VEHICLES AND VEHICLE SELECTION

In order to improve the knowledge of particulate emission behaviour in respect to current vehicle market and the available technologies, three vehicles in total were included in the experimental study. These three test vehicles were selected to represent typical gasoline-powered, modern vehicles available on the global market. The requirement was that the three test vehicles should cover at least following criteria (including examples):

- At least 1 most sold vehicle with mainstream technology (turbocharged, GDI, central mounted), e.g. VW Golf 1.5 l Euro 6d
- A small engine with big vehicle, e.g. VW Tiguan 1.5 l (and/or a loading of the vehicle to its maximum weight).
- A small vehicle with a large displacement engine
- An alternative technology: PFI naturally aspirated
- An advanced combustion technology, e.g. high injection pressure (300 bars): Hyundai Sonata 1.6 L GDI, Hyundai i30 1 l GDI
- Having an older vehicle with an aged GPF is a nice-to-have (not a must-have considering the difficulties of finding an “aged” Euro 6d vehicle).
- Focus on Euro 6d/6d-temp vehicles
- 2 tests per testing conditions is targeted (with a 3rd test only if repeatability is bad)
- Testing cycle: on a chassis-dyno, RDE-compliant, possibly with colder start and harsh accelerations.
- Mileage of test cars at start of test: 3,000-20,000km

Prior to the final vehicle selection, multiple vehicle models were inspected on a car jack to find suitable individuals that fit the purpose. The main criteria were to fulfil the above listed criteria, but also to find vehicles with a suitable engine aftertreatment system (EATS) configuration for performing extractive emissions sampling upstream the EATS. Furthermore, the engine and engine compartment layout of the test vehicles were examined for finding individuals with sufficient space for EO sampling as the vehicles were moved around several times between the conducted tests. In addition, automatic transmissions were favoured to minimize the deviation caused by driver behaviour caused by manual shifting.

14.1.1. Vehicle A

Vehicle A was selected to represent a typical, medium-sized passenger car that was equipped with a direct injected (GDI) engine and an automatic transmission. For this purpose, a VW Golf was selected (***Figure 14.1***). The VW Golf is a common medium sized passenger car and is the most sold vehicle model in Europe during the past three decades. The vehicle was equipped with a 1.5 litre turbocharged (TSI) engine combined with a 7-speed automatic DSG typed transmission. The EATS consisted of two TWCs (3-way catalyst) in combination with a gasoline particulate filter (GPF). The vehicle had an odometer reading of 6000 km in the beginning of the study and therefore required no excess break in. The main specifications of this test vehicle are described in more detail in ***Table 14.1***.

Figure 14.1 Vehicle A in the preparation facilities at VTT

Table 14.1 The main specifications of test vehicle A (VW Golf mk7)

Model	VW Golf (Mk7)
YM	2020
Emission class	DG, Euro 6d-TEMP-EVAP-ISC
Engine	1.5 l, 110 kW, TSI (GDI) turbocharged
Drivetrain	Automatic, 7-speed DSG
Mass of running order	1384 kg
Maximum total vehicle mass	1830 kg
EATS	2x 3-way catalysts + GPF
Mileage at the start of testing	~6000 km

14.1.2. Vehicle B

Vehicle B (***Figure 14.2***) represented a larger vehicle equipped with a smaller gasoline engine (1.2 litre GDI). The engine had been combined with an 8-speed "traditional" hydraulic transmission. The EATS of the vehicle consisted of one TWC and a GPF. Because this vehicle had only ca. 2000 km of total mileage at the time of procurement, the vehicle was broken in before the start of the test an additional 1000 km to fulfil the predefined 3000 km mark criteria. The main specifications of the test vehicle B are described in more detail in ***Table 14.2***.

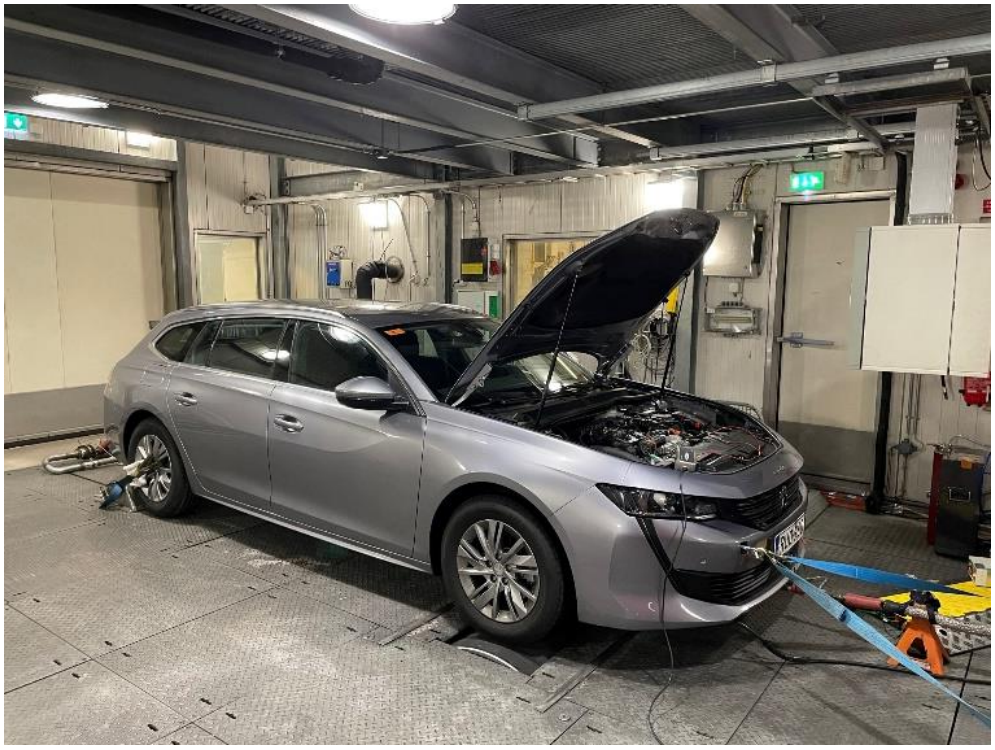


Figure 14.2 Vehicle B in the light-duty chassis dynamometer at VTT

Table 14.2 The main specifications of test vehicle B (Peugeot 508 SW)

Model	Peugeot 508 SW
YM	2020
Emission class	AP, Euro 6d ISC FCM
Engine	1.2 l, 96 kW, GDI, turbocharged
Drivetrain	Automatic 8-speed (hydraulic)
Mass of running order	1495 kg
Maximum total vehicle mass	2010
EATS	3-way catalyst + GPF
Mileage at the start of testing	~3000 km

14.1.3. Vehicle C

Vehicle C was the smallest vehicle of the three tested individuals. The vehicle was equipped with a small, 1 litre turbocharged port fuel injected (PFI) gasoline engine. Despite being PFI, the EATS consisted of a TWC and a GPF. Renault claims that the GPF has been installed on all 2021 PFI models to cover the requirements of the current low emission standards and the ISC criteria set for Euro 6d legislation. Vehicle C was equipped with an automatic transmission of the CVS and planetary type. The main specifications of the test vehicle C are described in more detail in ***Table 14.3***.

Figure 14.3 Vehicle B in the light-duty chassis dynamometer at VTT

Table 14.3 The main specifications of test vehicle C (Renault Clio)

Model	Renault Clio
YM	2021
Emission class	AP, Euro 6d ISC FCM
Engine	1.0 l, 67 kW, PFI, turbocharged
Drivetrain	Automatic (CVS + planetary)
Mass of running order	1190 kg
Maximum total vehicle mass	1614 kg
EATS	3-way catalyst + GPF
Mileage at the start of testing	~4000 km

14.1.4. Vehicle preparation for the experimental study

Each vehicle was prepared with emission sampling systems upstream and downstream EATS. In order to enable extraction of emission samples upstream EATS (engine-out emissions, EO), all vehicles were equipped with tailor made lambda (oxygen) sensor adaptors. The purpose of the adaptor was to enable upstream EO sampling through the lambda position but being able to maintain the original lambda-sensor position. The adaptor enabled both extractive emission sampling and EO temperature and pressure measurements. The adaptors were fabricated specifically for each vehicle ensuring proper sample line positions. An example of the lambda-adaptor fabricated for vehicle A is shown in ***Figure 14.4***. The exhaust flow of the extracted emissions sample and sample locations in the adaptor are shown in ***Figure 14.5***. The lambda-adaptor with the sample lines fitted in the vehicle A is shown in ***Figure 14.6***. Similar installations were applied for all three vehicles.

The tailpipe emissions of each vehicle were connected to the CVS system. Additional extractive lines for Fourier-transform infrared spectroscopy (FTIR) and PN samples were gathered prior to CVS. For calculating instantaneous emissions, an exhaust flow meter (EFM) was installed between the tailpipe and CVS. An overview of the tail pipe sampling is shown in ***Figure 14.7***.

Figure 14.4 The lambda adaptor for extracting the emission sample EO

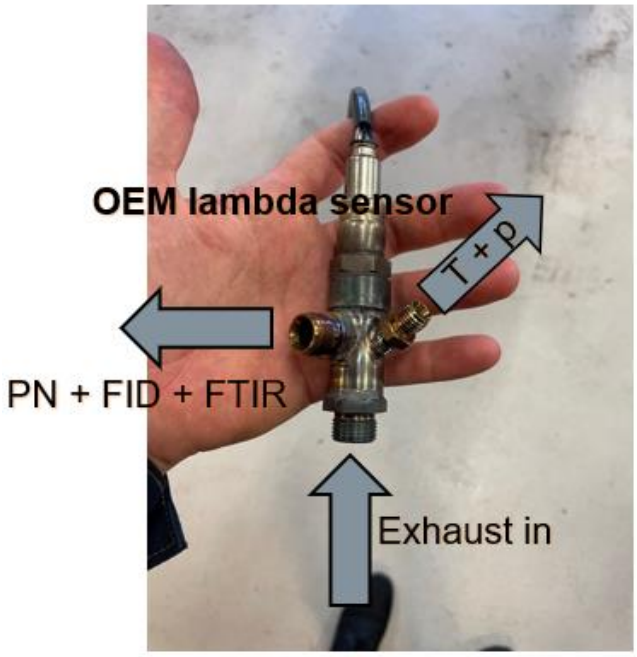


Figure 14.5 Direction of exhaust flow through the sample adaptor and OEM lambda sensor

Figure 14.6 The lambda-adaptor installed on vehicle A

Figure 14.7 Example of exhaust sampling to the CVS and FTIR

14.1.5. Assessment of initial vehicle condition

As the vehicles were set up for the experimental configuration through adding the lambda-adaptor for EO emissions sampling, each configuration was pre-tested according to the WLTP protocol and based on the road load values declared in the CoC. The main purpose for this action was to ensure the condition of test vehicles and that the vehicle emissions performance remain unchanged due to the measurement configuration, such as addition of EO sampling and small changes in lambda-sensor position caused by the lambda adaptors. The WLTP emission values obtained from the CoC and test results both as baseline and as full test configuration are shown in ***Table 14.4***, ***Table 14.5*** and ***Table 14.6***. The main conclusion from the initial assessment was following:

- For vehicle A and B, the CO_2 values were found somewhat lower than declared in respective CoC
- CO and NO_x emissions were typically found somewhat lower for the test results compared to the CoC for all vehicles.
- Greatest deviation between the baseline and full test configuration was found for vehicle C, yet no significant indication of abnormal behaviour of the given vehicle and was rather considered as natural variation caused by vehicle technology.

Table 14.4 Results from the initial assessment with WLTP protocol in respect to the CoC values for vehicle A

Vehicle A, VW Golf							
Configuration	CO2	CO	THC	NMHC	NOx	PN	PM
	(g/km)	(mg/km)	(mg/km)	(mg/km)	(mg/km)	(#*10^11/km)	(mg/km)
CoC	142.0	168	20	17	32		
Baseline	134.2	64	18	15	16		0.12
Full test configuration	131.6	66	15	13	14		0.19

Table 14.5 Results from the initial assessment with WLTP protocol in respect to the CoC values for vehicle A

Vehicle B, Peugeot 508							
Configuration	CO2	CO	THC	NMHC	NOx	PN	PM
	(g/km)	(mg/km)	(mg/km)	(mg/km)	(mg/km)	(#*10^11/km)	(mg/km)
CoC	136.0	341	20	17	38	2.3	0.30
Baseline	127.0	323	28	26	13		0.09
Full test configuration	126.5	286	27	28	21		0.19

Table 14.6 Results from the initial assessment with WLTP protocol in respect to the CoC values for vehicle A

Vehicle C, Renault Clio							
Test type	CO2	CO	THC	NMHC	NOx	PN	PM
	(g/km)	(mg/km)	(mg/km)	(mg/km)	(mg/km)	(#*10^11/km)	(mg/km)
CoC	129.0	258	32	29	28		
Baseline	129.7	154	66	62	13		<0.1
Full test configuration	124.0	292	52	49	12		< 0.1

14.2. TEST FUELS

For the experimental part, ten fuels with different fuel characteristics were included in the study. Two of the tested fuels were included in the previous particulate emission study coordinated by Concawe. The given fuels were chosen by the Concawe members to be representative of fuel properties found in EU FQD survey. The analysis of each fuel type was delivered to VTT prior to the start of the experimental study. The fuels were later named for easier identification according to ***Table 14.7***. The boiling range (distillation curve) is shown for all test fuels in ***Figure 14.8***. ***Table 14.8*** express the content of olefins, aromatics, oxygen, ethanol, ETBE and MTBE in respect of each test fuel. A more comprehensive list of all fuel characteristics is presented in Appendix A

Table 14.7 A list of fuel names, type, grade

Fuel Code	Type	Grade
Fuel 1	UL95-E10	Summer
Fuel 2	UL98-E5	Summer
Fuel 3	UL98-E5	Winter
Fuel 4	Splash blend E10	Winter
Fuel 5	Splash blend E10	Winter
Fuel 6	Splash blend E20	Winter
Fuel 7	UL95-E5	Winter
Fuel 8	UL95-E10	Winter
Fuel 9	UL95-E5	-
Fuel 10	UL95-E5	-

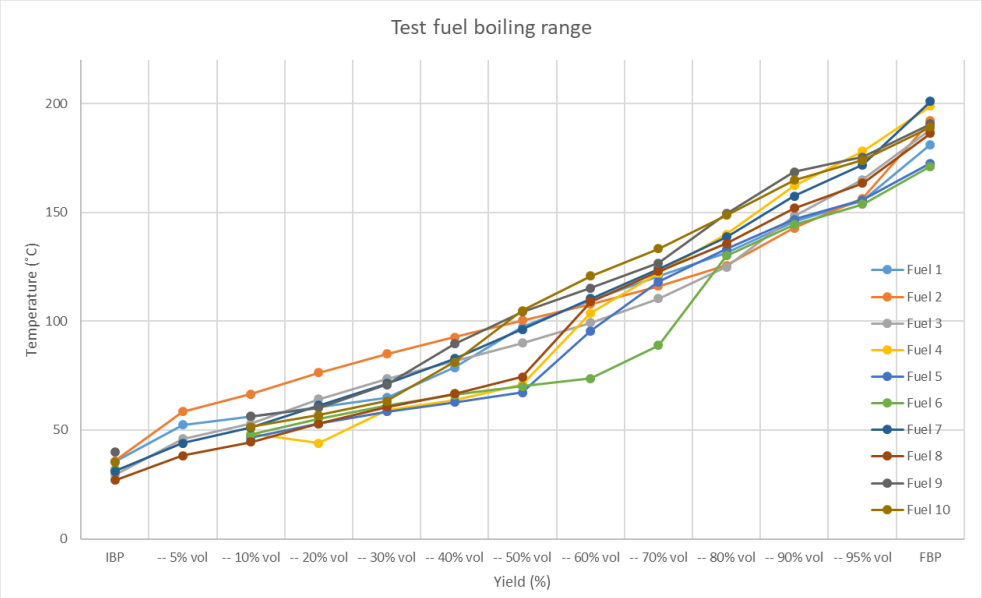


Figure 14.8 The boiling curve of the ten test fuels

Table 14.8 The content of olefins, aromatics, oxygen, ethanol, ETBE and MTBE in respect of all test fuels

Fuel Code	Olefins (%v/v)	Aromatics (%v/v)	C9 and C9+ arom (% v/v)	<C9 Aromatics (% v/v)	Oxygen (%m/m)	Ethanol (%v/v)	ETBE (%v/v)	MTBE (%v/v)
Fuel 1	12.4	27.8	7.8	20.1	3.6	7.9	7.3	0.2
Fuel 2	2.3	22.0	7.3	14.7	2.6	0.0	17.7	0.0
Fuel 3	4.0	34.4	12.0	22.4	2.6	0.2	18.8	0.0
Fuel 4	12.9	28.4	12.5	15.9	3.7	9.9	0.0	0.0
Fuel 5	8.3	35.0	9.9	25.1	3.8	10.2	0.0	0.1
Fuel 6	7.3	31.4	8.9	22.5	7.4	19.3	0.0	0.0
Fuel 7	7.4	33.1	12.5	20.5	0.9	0.0	0.1	4.9
Fuel 8	7.0	31.6	11.9	19.7	3.7	9.7	0.0	0.5
Fuel 9	10.5	20.5	5.5	15.0	2.7	5.1	5.1	0.0
Fuel 10	10.7	33.9	9.8	24.1	2.7	5.3	5.0	0.0

14.3. TEST MATRIX

The test matrix was prepared and designed by Concawe. The test order of the test fuels was designed to be tested in a random order to minimize the potential deviation caused by changes in vehicle behaviour (e.g. vehicle settling). Each fuel was tested at least two times, apart from “reference fuels” which were tested at least after every 5 other fuels had been tested. All three vehicles were nominated with different reference fuels, Fuel 1 for vehicle A, Fuel 7 for vehicle B and Fuel 5 for vehicle C. The test matrix was designed to be tested in two clusters shown in ***Table 14.9***

Table 14.9 Original test matrix design divided into two clusters, 1sr and 2sr

VTT fuel test order -1sr		
A	B	C
Fuel 1	Fuel 7	Fuel 5
Fuel 2	Fuel 6	Fuel 7
Fuel 3	Fuel 10	Fuel 1
Fuel 4	Fuel 8	Fuel 9
Fuel 5	Fuel 9	Fuel 4
Fuel 6	Fuel 2	Fuel 8
Fuel 1	Fuel 7	Fuel 5
Fuel 7	Fuel 10	Fuel 10
Fuel 9	Fuel 3	Fuel 3
Fuel 10	Fuel 1	Fuel 2
Fuel 8	Fuel 5	Fuel 6
Fuel 1	Fuel 7	Fuel 5

VTT fuel test order -2sr		
A	B	C
Fuel 1	Fuel 7	Fuel 5
Fuel 6	Fuel 6	Fuel 2
Fuel 7	Fuel 3	Fuel 1
Fuel 10	Fuel 1	Fuel 10
Fuel 5	Fuel 9	Fuel 3
Fuel 2	Fuel 2	Fuel 7
Fuel 1	Fuel 7	Fuel 5
Fuel 3	Fuel 5	Fuel 6
Fuel 9	Fuel 10	Fuel 4
Fuel 4	Fuel 8	Fuel 8
Fuel 8	Fuel 3	Fuel 9
Fuel 1	Fuel 7	Fuel 5

Some of the tests conducted during the study were completely discarded due to vehicle abnormal failure. Additionally, some test included non-complete data, but these were mostly processed in the data assessment normally, if the data missing was not related to particulate emissions. The final test matrix was therefore adapted according to the failures along the experimental process, and completely discarded or failed tests were repeated after the two original test clusters had been completed. Furthermore, tests with high deviation were later studied and if seen justified, were discarded later during the data assessment. However, at least two repetitions for each fuel/vehicle configuration were ensured to be included in the data assessment. The processing methods and data assessment are described in more detail in chapter *Data analysis and post processing methods*. The final test matrix is shown in ***Table 14.10***, including an additional test cluster covering for the excess tests performed due to discarding of data. The successful tests are marked in ***Table 14.10*** as green. Test that were cosidered as completely discarded due to vehicle behaviour related issues are marked in the table as red or yellow depending of the discarding reason. Cells marked in orange describes that the test had a non-complete but still valid emission result with missing data e.g. from non particulate related origin. The main criteria for the above mentioned scenarios may be divided into following reasons:

- During the first test cluster, a malfunction in the TP FTIR occurred. Therefore no FTIR data was obtained (neither NH_3 nor N_2O). These tests are marked as orange.
    - The FTIR was replaced with another available FTIR, however, the results obtained with the two FTIR:s were not directly comparable due to differences in response time and detection limit. Therefore, no FTIR results were analysed in depth (in respect to fuel properties), but were sampled to confirm and follow the general condition of each test vehicle.
- When performing cluster two, vehicle A was gradually discovered to behave abnormally, albeit no error signals were transmitted to the dashboard nor driver. However, plugged in a OBD-tester, an engine speed limiter (4000 rpm) was found active. The issue was found to be related to constant fuel

changes, as some air in the fuel lines was suspected to trigger a fuel rail pressure alarm. After deleting these error codes no further issues were found with vehicle A. These tests are marked in cluster two in yellow.

- A gradual increase in TP PN emissions was found for vehicle C in cluster two. However, no signs of error codes appeared on the generic OBD-tester. Eventually, the PN emissions were found to be caused by a crack in the lambda-adaptor, allowing excess air to enter to the vicinity of the lambda-sensor disturbing the lambda-sensor signal with dilution air, thus resulting in unproper enrichment of the air/fuel mixture. The reason of the crack was found to be caused by significant engine vibrations of the three cylinder engine. The crack in the lambda-adaptor was re-welded and reinforced, which eventually resolved the issue and restored the vehicle behaviour to a normal state. The test that were influenced by the adaptor failure are marked in cluster two for vehicle C in yellow.

Table 14.10 The final test matrix including an additional test cluster compensating for discarded tests

VTT fuel test order -1sr			VTT fuel test order -2sr		
A	B	C	A	B	C
Fuel 1	Fuel 7	Fuel 5	Fuel 1	Fuel 7	Fuel 5
Fuel 2	Fuel 6	Fuel 7	Fuel 6	Fuel 6	Fuel 2
Fuel 3	Fuel 10	Fuel 1	Fuel 7	Fuel 3	Fuel 1
Fuel 4	Fuel 8	Fuel 9	Fuel 10	Fuel 1	Fuel 10
Fuel 5	Fuel 9	Fuel 4	Fuel 5	Fuel 9	Fuel 3
Fuel 6	Fuel 2	Fuel 8	Fuel 2	Fuel 2	Fuel 7
Fuel 1	Fuel 7	Fuel 5	Fuel 1	Fuel 7	Fuel 5
Fuel 7	Fuel 4	Fuel 10	Fuel 3	Fuel 5	Fuel 6
Fuel 9	Fuel 3	Fuel 3	Fuel 9	Fuel 10	Fuel 4
Fuel 10	Fuel 1	Fuel 2	Fuel 4	Fuel 8	Fuel 8
Fuel 8	Fuel 5	Fuel 6	Fuel 8	Fuel 4	Fuel 9
Fuel 1	Fuel 7	Fuel 5	Fuel 1	Fuel 7	Fuel 5

VTT fuel test order - spare tests		
A	B	C
Fuel 5	Fuel 3	Fuel 2
Fuel 2	Fuel 6	Fuel 1
Fuel 3	Fuel 7	Fuel 10
Fuel 4	Fuel 7	Fuel 3
Fuel 1		Fuel 1
		Fuel 10
		Fuel 7
		Fuel 5

Succesful test
Test completed, some test data missing*
Necessary data missing**
Abnormal vehicle behaviour
*e.g. FTIR failure
**e.g. CVS-sampling failure

14.4. TEST CYCLE

VTT used a test cycle that was sourced from an existing PEMS test route typically executed by VTT. The used vehicle in this test session was a similar type of a vehicle and the chosen test fulfilled all required criteria for a compliant RDE test. To save some testing time VTT shortened the test slightly by cutting some parts off from the test data. Despite the cutting, the shortened test cycle still fulfilled the criteria. In order to enable CVS emissions bag sampling, the test cycle was divided into four phases. The phases were divided based on the available sample time, bag sample volume and suitable moments in the speed profile.

The original test was around 6100 seconds long (

Figure 14.9) and the shortened version was 5545 seconds long (***Figure 14.10***). Even though the gradient for the RDE compliancy does not have many requirements, VTT used realistic gradient for the test cycle. The road gradient of the original RDE test was directly transferred to the dynamometer test. The gradient in respect to vehicle speed is shown in ***Figure 14.11***. The central information for each sampling phase is shown in ***Table 14.11***. The last phase change occurs while the speed was at relatively steady speed, but the other two occur when the vehicle is "stationary" on the rollers.

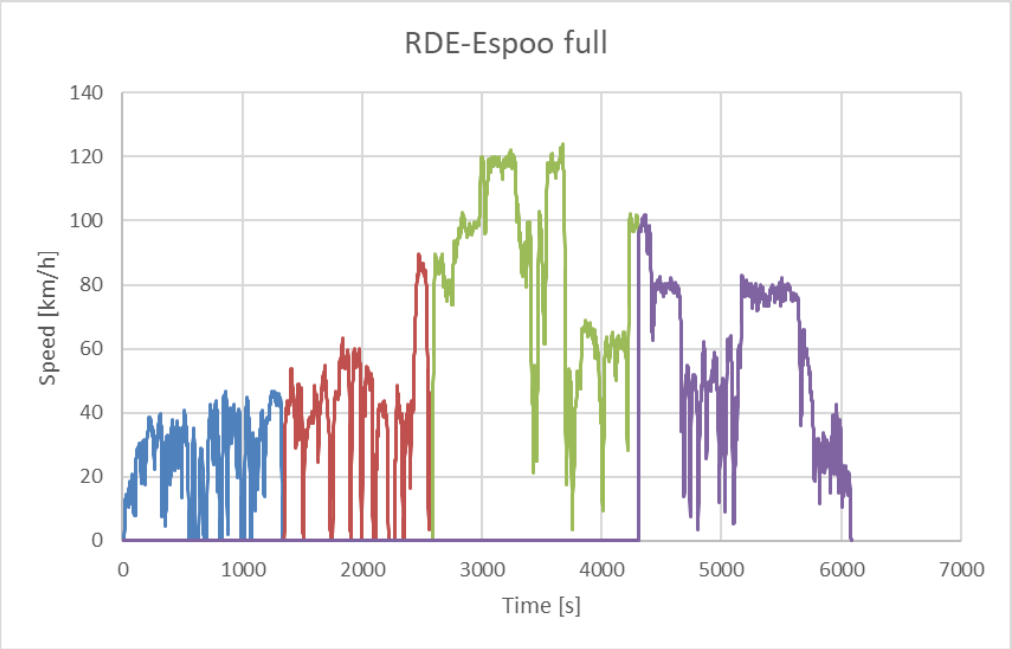


Figure 14.9 Original test cycle

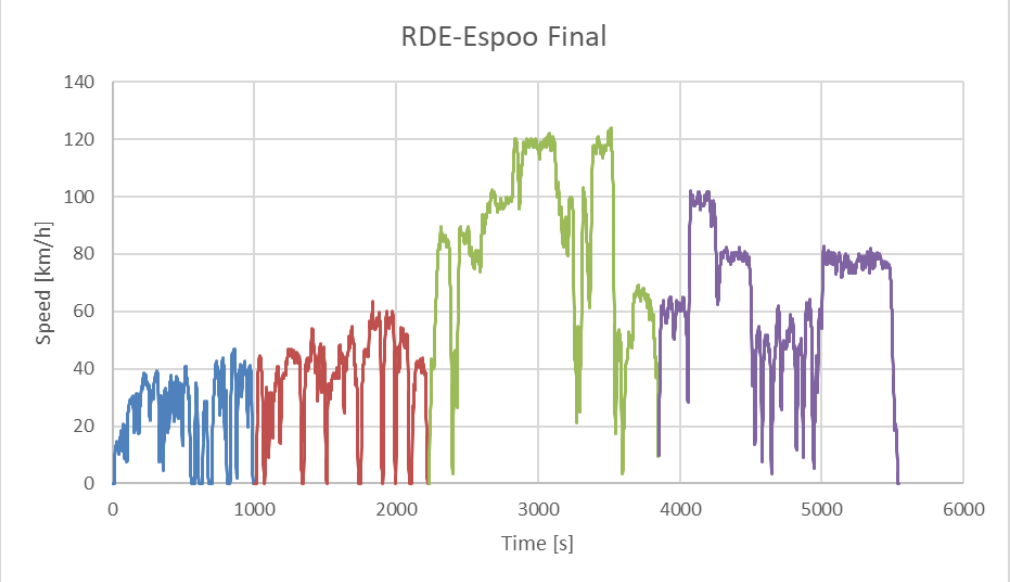


Figure 14.10 Shortened test cycle

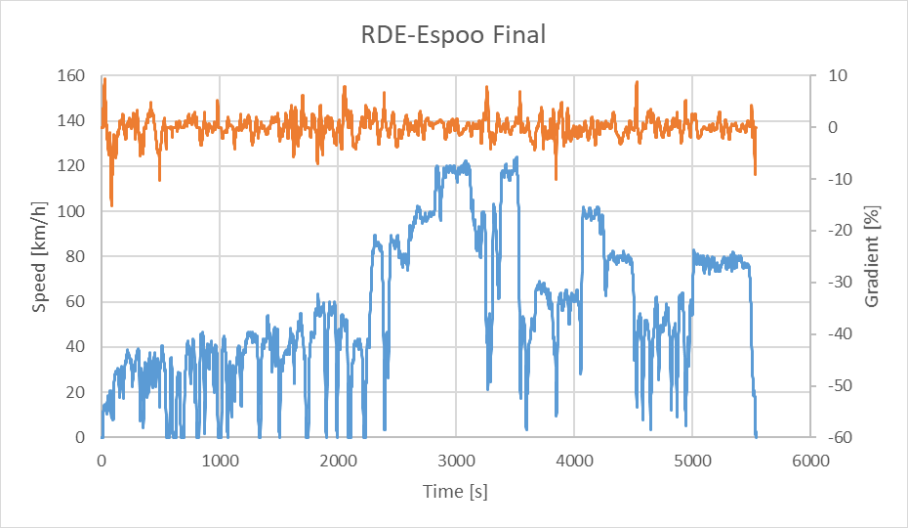


Figure 14.11 Test cycle with gradient

Table 14.11 Average time and speed profile of each phase of the RDE test

	Time [s]	Time [min]	Average speed [km/h]
Phase 1	1000	16.7	21.3
Phase 2	1230	20.5	36.8
Phase 3	1621	27.0	84.4
Phase 4	1694	28.2	65.4
Total	5545	92.4	55.7

14.5. TEST SETUP AND MEASUREMENT DEVICE CONFIGURATION

14.5.1. Test layout

The test layout was set in a way that measurements from both EO and TP data could be sampled simultaneously. The EO measurements were conducted by extracting an emission sample flow prior to the EATS of each vehicle, and the concentrations (sec by sec) were proportioned to the instantaneous exhaust mass flow rate sampled by a pitot type exhaust flow meter (EFM).

The raw exhaust gas measurement was done using the relocated oxygen sensor. This sampling route was split in three ways. Before the split a large diameter (12/10 mm) heated sampling line was used. Each route had their own sampling pump. One way was used for the FTIR unit (BOB-1000FT). The second way was used by the FID unit. The third way was used by the particle sampling. The particle sampling setup consisted of three dilution units in series (Dekati eDiluter Pro followed by two Dekati DI-1000 ejector diluters). The dilution ratio of the eDiluter Pro was set to 225 and dilution air temperature to 350 °C in all measurements. The dual ejector diluter setup had dilution ratio of 49. Two condensation particle counters (10 nm CPC A20 and 23 nm CPC A23, Airmodus Oy) sampled from the output of the last ejector diluter.

The tail pipe FTIR sampling point was located just after the vehicles' original exhaust pipe. The exhaust temperature and the pressure difference were also measured from this area. The pressure difference was measured between this point and the sampling point in the oxygen sensor location. The raw (tracer) CO_2 point was located just before the junction for the raw exhaust gases and the dilution air.

The rest of the sampling was conducted from the dilution tunnel. The AVL devices use their own and dedicated sampling system (for CO, CO_2, NO, NO_x and PM). The particle measurements were conducted by diluting the sample from the dilution tunnel with Dekati Engine Exhaust Diluter (DEED, Dekati Oy). The diluter has two selectable dilution rations and one of them, low dilution ratio (PCRF 88) was used for all tests. After the DEED, exhaust particles were measured with two CPCs in parallel (10 nm CPC A20 and 23 nm CPC A23, Airmodus Oy). Electrical low-pressure impactor (ELPI, Dekati Oy), equipped with a filter stage, was also measuring particles from the DEED.

Measurement configuration:
EO measurements
CO_2, CO, NO_x, THC, PN_{23}, PN_{10}, EGT and upstream EATS back pressure (pressure difference to tailpipe)

TP measurements
CO_2, CO, NO_x, THC, NH_3, N_2O, PN_{23}, PN_{10}, particle size distribution, EGT, exhaust mass flow.

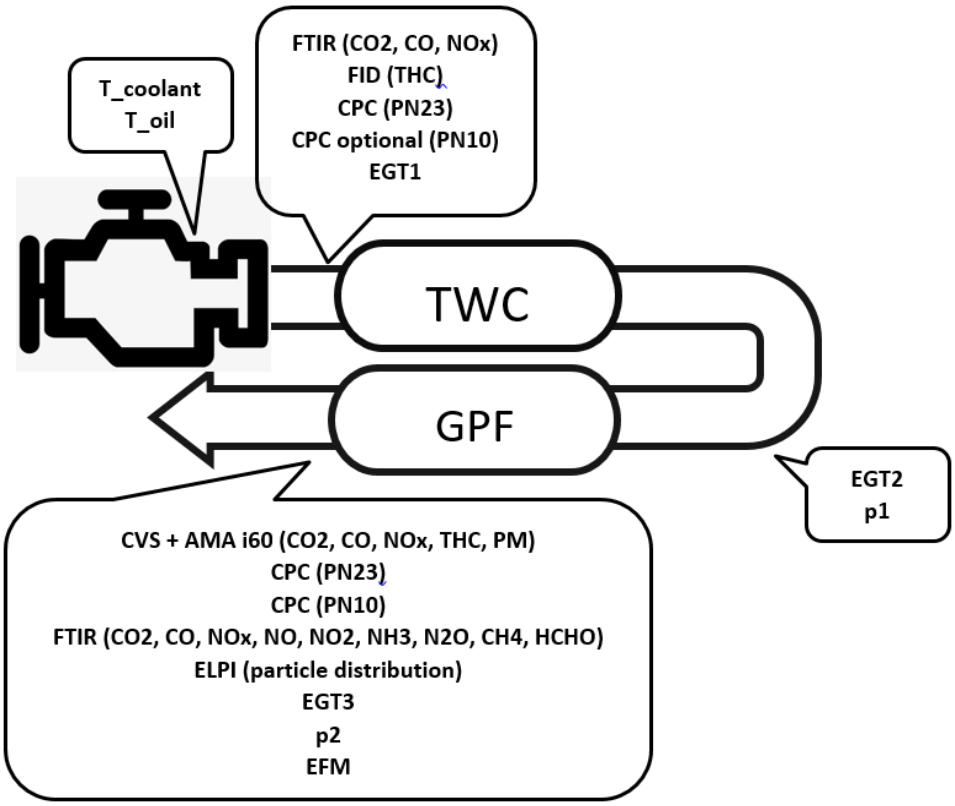


Figure 14.12 An illustration of the emission measurement configuration

14.5.2. Emission analysers and measurement equipment

This chapter describes the emissions analysers and other measurement equipment used in the study. The main specifications of the measurement equipment are:

Light-duty chassis dynamometer:
Manufacturer: Froude Consine Ltd
Maximum power: ± 100 kW (160 km/h)
Inertia simulation range: 450 – 2 750 kg
Diameter of the dynamometer rollers: 1 m

Emission sampling and dilution system:
Manufacturer: AVL
CVS: AVL CVS i60Multiple (4) CFV-venturi system
Flow: 3-18 m3/min
Particle mass (PM) collector: AVL PSS i60
Emission analyser system: AVL AMA i60, with the following analysers:
FID i60 LHD (THC): 0..3 ppm / 0...1000 ppm
FID i60 LHD (CH4): 0..9 ppm / 0..1000 ppm
CLD i60 LC (NO/NOx): 0..3 ppm / 0..1000 ppm
CLD i60 LH (NO/NOx): 0..3 ppm / 0..1000 ppm
IRD i60 L (CO): 0..50 ppm / 0..5000 ppm
IRD i60 H (CO2): 0..0,1 % / 0..5.8 %
IRD i60 L (CO2 tracer):0..0,5 % / 0..20 %

Fourier Transformation Infra-Red (FTIR), TP measurements:
Supplier: Rowaco
Temperature controlled sample cell (190°C)
Liquid nitrogen cooled MCT detector
Spectral resolution: 0.5 cm-1
Path length: 5.11 m
Sampling speed: 1 Hz
Sample cell volume: 200 ml
N2O detection limit: 0.4 ppm
NH3 detection limit: 0.4 ppm
NO detection limit: 1 ppm
NO2 detection limit: 0.6 ppm

Fourier Transformation Infra-Red (FTIR), EO measurements:
Supplier: A&D (BOB-1000FT)
Measuring Method: FTIR
Measuring components: 24 Components standard, up to 30 optional
Application: Gasoline/Diesel Direct
Dimensions: Approximately 482(W) x 645(D) x 391(H)mm
Operating Conditions: 5-40°C, Relative Humidity 80% (non-condensing)
Sampling Frequency: 1 Hz and 5 Hz (selectable)
Absorbance Spectrum: 500-5000 cm-1
Spectral Resolution: 0.5 cm-1
Optical Path Length: 5.1 m
Gas Cell Volume: 200 ml
Gas Cell Temperature: 191°C
Detector Cooling Method: MCT Liquid Nitrogen, 50 ml/h
Response Time (T10-T90): 1.5 - 2.0 sec
Zero Drift: 1.0% F.S./4 h = (±5°C)

Span Drift: 1.0% F.S./4 h = (±5°C)
Repeatability: 2.0% F.S

Fourier Transformation Infra-Red (FTIR)
Supplier: Gasmet (Cr-2000)
Temperature controlled sample cell (180°C)
Liquid nitrogen cooled MCT detector
Resolution: 8 cm-1
Path length: 2.0 m
Sample cell volume: 0,22 l
N2O detection limit: 4 ppm
NH3 detection limit: 3 ppm

Exhaust dilution for PN and size distribution measurements from preEAT (EO)
Dekati eDiluter Pro
Dilution ratio: 5 x 5 = 25 to 15 x 15 = 225
Hot primary dilution up to 400 °C (VTT operates normally at 350 °C)
Inlet flow rate: 4 – 10 l/min

Additional dilution for preEAT PN measurement
Dekati Diluter DI-1000
Dilution ratio: ~7
Inlet flow rate: ~6 l/min

Exhaust dilution for PN and size measurements
Dekati DEED
Dilution ratio: ~100 or ~1000
Inlet flow rate: ~7 l/min

Particle number measurement PN >23 nm
Condensation Particle Counter (CPC): Airmodus A23
Particle size range: 23 nm – > 2.5 µm
Particle concentration: 0 – 100 000 1/cm3
Response time: 1.15 s
Sampling speed: 1 Hz
Inlet flowrate: 1 l/min

Particle number measurement PN >10 nm
Condensation Particle Counter (CPC): Airmodus A20
Particle size range: 10 nm – > 1 µm
Particle concentration: 0 – 100 000 1/cm3
Response time: 1.15 s
Sampling speed: 1 Hz
Inlet flowrate: 1 l/min
Instruments available at VTT: 1 (+1 leased as an option)

Particle size distribution measurement
Electrical Low-Pressure Impactor (ELPI): Dekati ELPI
Particle size range 7 nm –10 µm, 12 size fractions
Response time: ~ 3 s
Sampling speed: 1 Hz
Inlet flow rate: 10 l/min
Instruments available at VTT: 2

Fuel consumption was primarily defined based on the carbon balance, but gravimetric measurements also took place, using the following scale:

Exhaust flow sampling
EFM (Exhaust Flow Meter): AVL

Flow rates

Pipe size	Flow rates at 100 °C	Flow rates at 400 °C
2"	15 … 570 kg/h	23 … 430 kg/h

Linearity

$| X_{min} \times (a_1 - 1) + a_0 | < 1.0\%$ of full scale;
Slope: $0.98 \leq a_1 \leq 1.02$; SEE: ≤ 2% max; R^2: ≥ 0.990

Flow measurement accuracy

±2.0% of reading or ±0.5% of full scale, whichever is greater

14.6. DATA ANALYSIS AND POST PROCESSING METHODS

14.6.1. Emission calculations and data post processing

Prior to the data assessment, each test was specifically post processed from raw data into mass-based results. The post processing was including data synchronization and emission calculation from either the CSV or the EFM depending on emission component. The raw exhaust flow was measured using the EFM flow measurement and it was also calculated using the carbon balance method. This method uses raw and diluted CO_2 concentrations to estimate the raw exhaust gas flow. The EFM tube measurement failed in two of the tests and the carbon balance method was used with these, but the EFM results were used with the rest.

The calculation was done by first time synchronizing the raw data manually using data plots. Suitable data channel was used for the synchronization. CO_2 emissions were measured using several different instruments, so their synchronization is the most critical part. The vehicle speed, EFM and PN data can be easily aligned with the CO_2 data. As the sampling points are located several meters apart from each other and the exhaust mass flow varies during a test session, a perfect synchronization during all moments is impossible to accomplish. So the main emphasis for the synchronization was done using the moments in the test cycle that produce a high amount of exhaust emissions and contains suitable peaks in the plots (at 4700-5000 seconds from the start). During the synchronization suitable matching peak are aligned using plots. The raw FID data had to be synchronized at the early parts of the test as the data was nearly flat after 200 seconds. Example synchronization cases can be seen in ***Figure 14.13*** and ***Figure 14.14***.

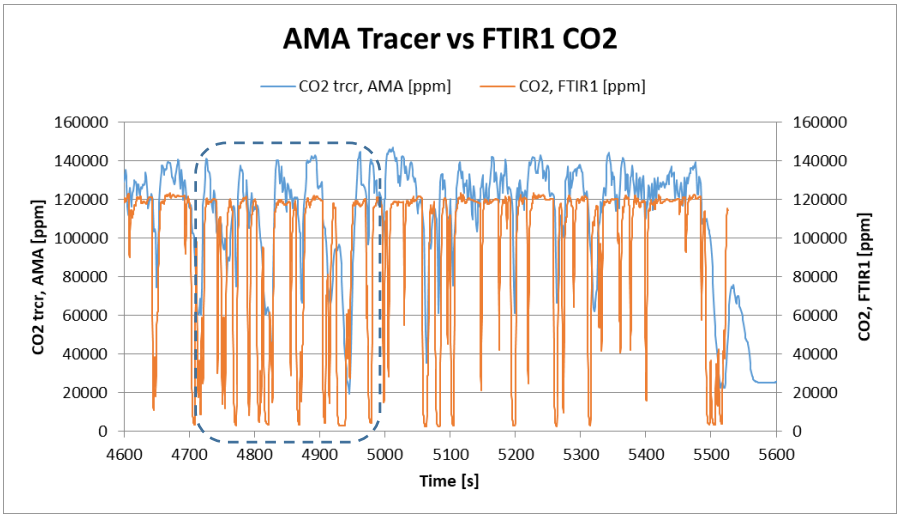


Figure 14.13 An example of data synchronization based on AMA Tracer vs FTIR response

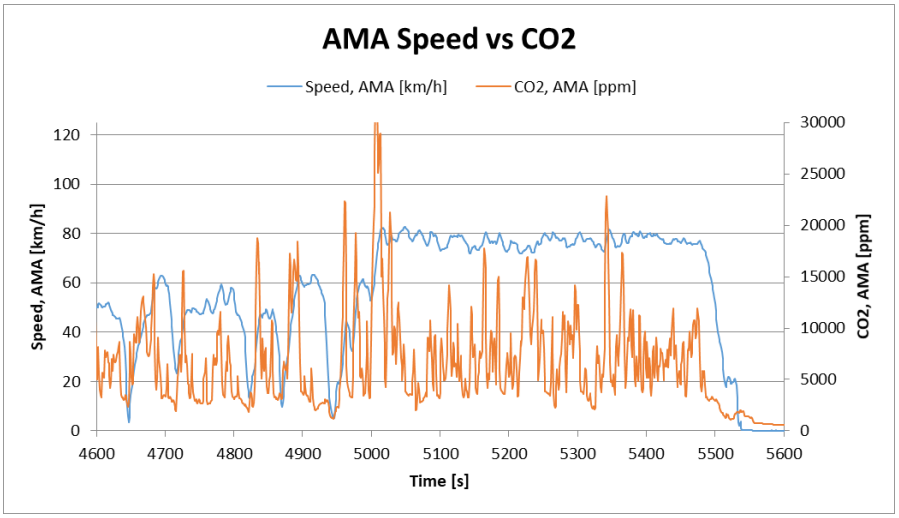


Figure 14.14 An example of synchronization of speed vs CO2 data based on AMA data

The data processing was done in steps. The sample bag and the particulate mass filter for each tests used the normal VTT method. The next step was to gather all real time data in a single file. Then the synchronized data was added to the calculations. The final step was calculating the results for each test phase and each test. Besides the predetermined 4 phases, 5 additional test parts were also calculated (2 rural parts, 2 motorway parts and 1 highway part).

All of the calculated data was finally combined into single files for each test. The key values for the test were used to make the final compilation files for the entire test campaign. Some of the test had to be disregarded due to the missing input data for the calculations but the rest were chosen from final data compilation.

15. PHASE 2 - TEST RESULTS

15.1. AN OVERVIEW OF GATHERED EXPERIMENTAL DATA

The data acquired from the tests were analysed initially in chronological order to ensure no abnormal behaviour of any vehicle/fuel combination occurred. Furthermore, when at least two successful tests per vehicle/fuel combination were obtained, the average results from the fuel specific non-discarded results were calculated, expressing the fuel effect caused from each test fuel. The variations in fuel consumption for each fuel was treated as a noise. These are indicated in all figures in the form of error bars. The noise was defined by calculating the standard deviation for all fuels. It should be noted that in most cases only two successful tests were obtained, thus the standard deviation of the two tests expresses only the deviation for the two tests in respect to the average result. A summary of the experimental results is shown in more detail in Appendix B.

15.1.1. Data validation and repeatability analysis

The main objective of the experimental study was to produce at least two successful repetitions for each fuel/vehicle combination. Additionally, the reference fuels, which were tested after five test fuels, were completed. The purpose of performing additional repetitions for reference fuels was to ensure the test repeatability and to check for any inconsistencies throughout the test matrix. Each matrix started and ended with test of reference fuel. The tests were validated using several criteria, but one fundamental basis was trend analysis of the results based on the chronological test order. The overall assessment of the test repeatability was defined based on few criteria:

- Stability of trip work and trip distance
- Validity of vehicle behaviour
- Emission analyser consistency
- Analysis of the energy consumption using the CO_2 based emission factor calculation

If any inconsistencies were found, the results were analysed in more detail. If any crucial inconsistencies were found, the test was discarded and renewed after the original test matrix was completed. This rule applied likewise for any inconsistency of emission result or if any key results were missing due to analyser failure.

An example of the inconsistency in trip distance is shown for each vehicle in ***Figure 15.1***, ***Figure 15.2*** and ***Figure 15.3***. For these tests, the original driver was replaced by a reserve due to COVID-19. Due to the inconsistency in trip distance (and thus work) caused by the change in driving behaviour, these specific results were discarded from the analysis.

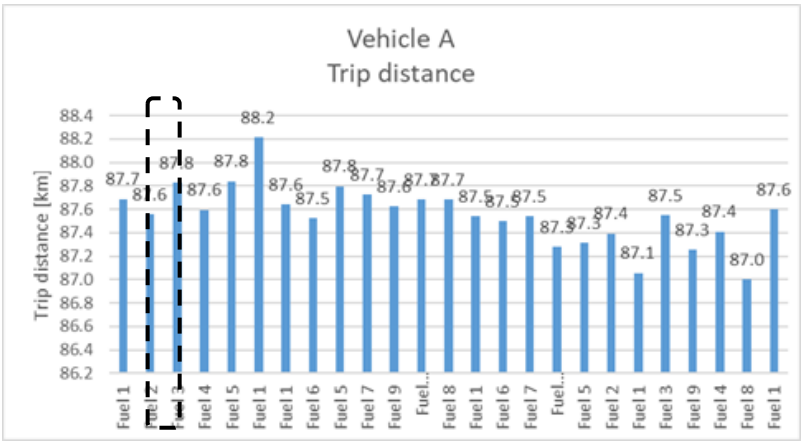


Figure 15.1 Trip distance for vehicle A (chronological test order)

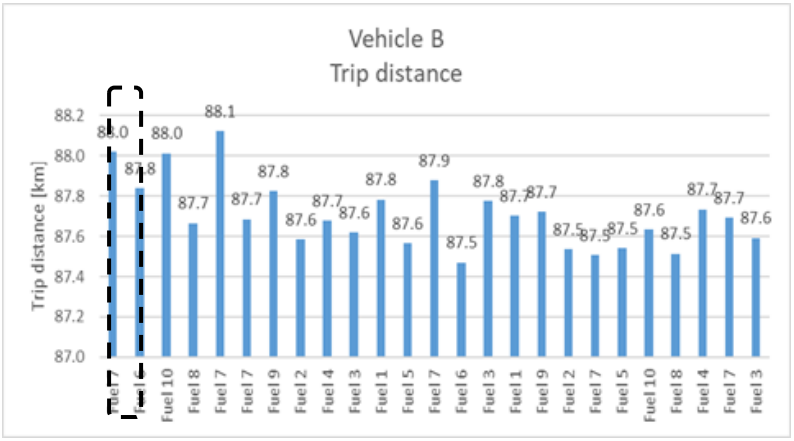


Figure 15.2 Trip distance for vehicle B (chronological test order)

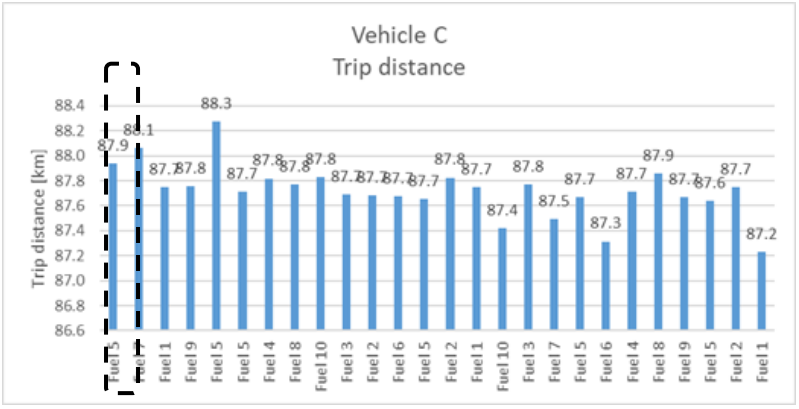


Figure 15.3 Trip distance for vehicle C (chronological test order)

15.1.2. Gaseous emissions

This chapter describes the acquired gaseous emission results obtained from the experiments. CO_2 emissions are generally dependent of two main factors, fuel CO_2-factor and engine/drivetrain performance, i.e. fuel efficiency. Any fuel-related trends may, however, be distinguished by analysing the cross correlation of the emissions between vehicle to vehicle. The CO_2 results obtained for each vehicle are shown in

Figure ***15.4***, Figure 15.5 and Figure 15.6. The CO_2 emissions were found relatively stable throughout the tests with some exceptions: fuel 3 and fuel 7 caused most distinguishable deviation with vehicle B. Correspondingly, highest deviation for CO_2 was seen for vehicle C for fuel 1. The dominant reason for these abnormal deviations remains unclear, as no indication of significant variance in powertrain work nor trip distance could exclusively explain these deviations. Nevertheless, vehicle A produced most stable results, with relatively constant deviation in CO_2 emissions.

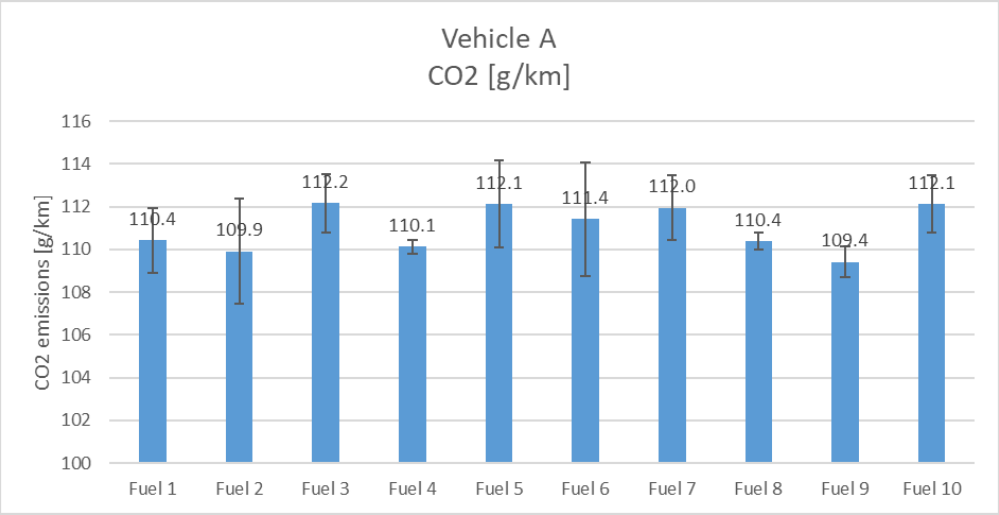


Figure 15.4 Average fuel specific CO_2 results for vehicle A

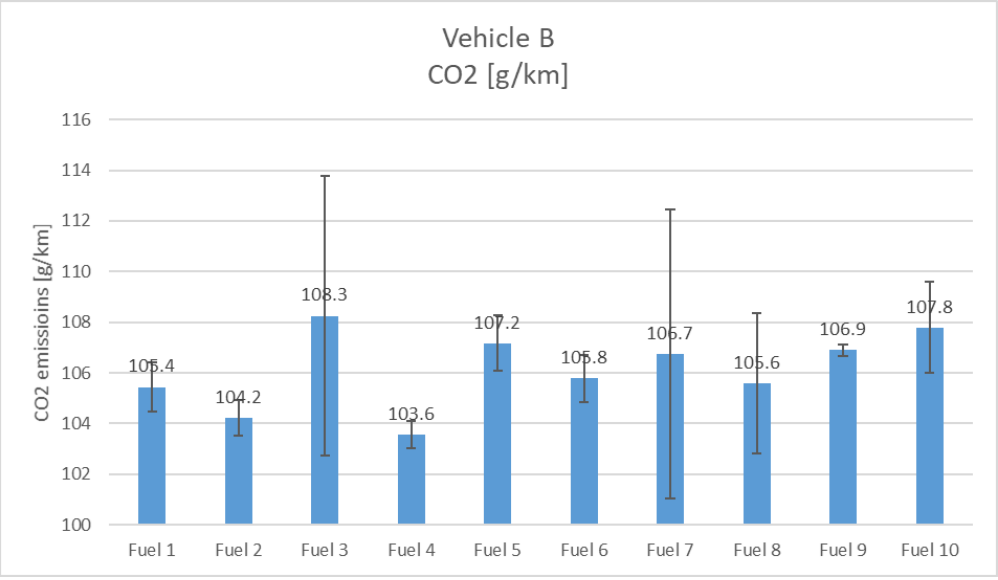


Figure 15.5 Average fuel specific CO_2 results for vehicle B

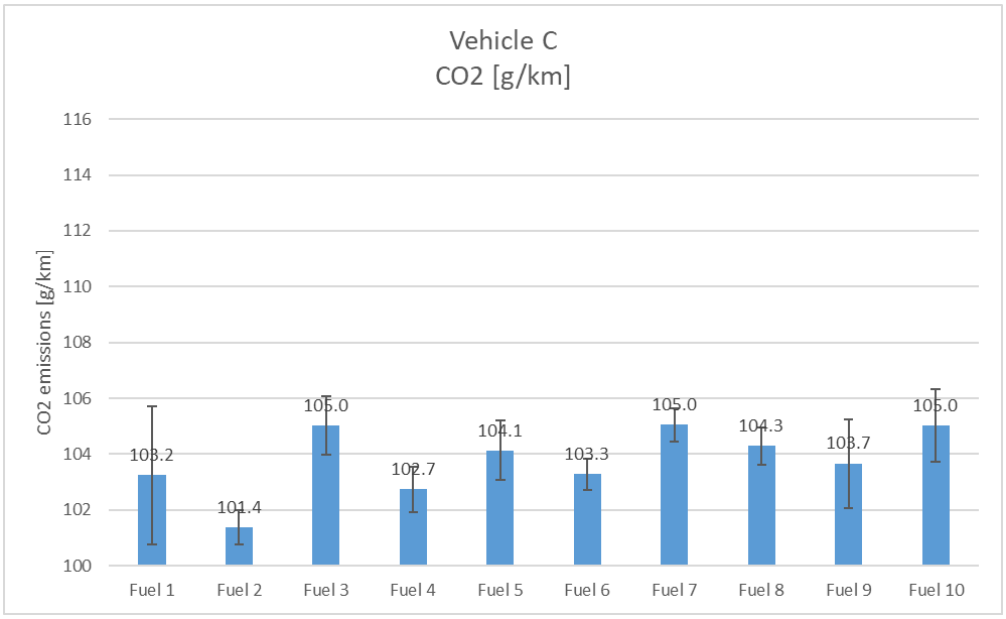


Figure 15.6 Average fuel specific CO_2 results for vehicle C

The response for given fuel changes were analysed by examining the linear correlation for the CO_2 results between the tested vehicles. The correlation between the CO_2 response is shown in Figure 15.7. Each point resembles an average value of test measurements conducted for a single fuel for two vehicles. Despite the trends in CO_2 behaviour is somewhat distinguishable, the correlation in CO_2 behaviour was found relatively poor (R^2 below 0.5 for vehicle A and vehicle B and C), thus no decisive conclusions of fuel effect could be withdrawn. The correlation between B and C were found greatest, albeit the R^2 value was below 0.7. The total trip energy consumption for each fuel was calculated per vehicle by using the CO_2 emission factors declared by Concawe.

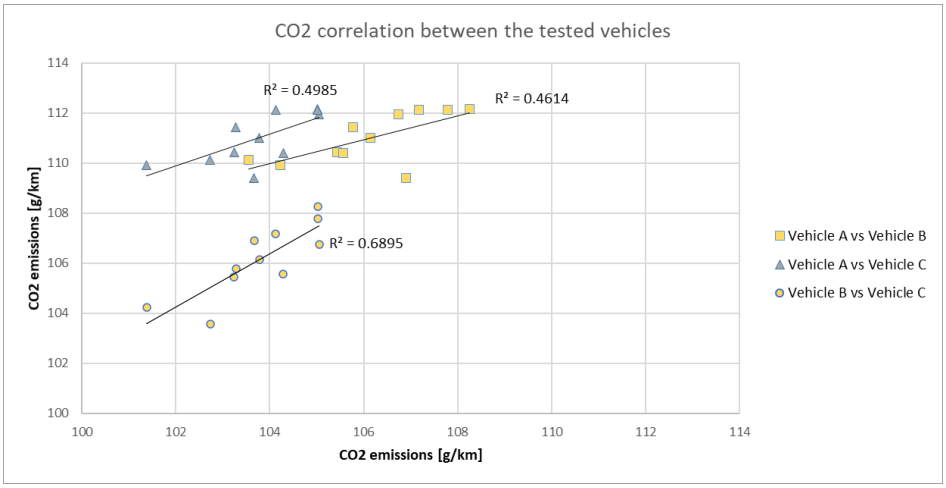


Figure 15.7 Correlation of CO_2 results between the tested vehicles

By converting the corresponding CO_2 results into energy consumption (by using the declared CO_2 emission factors), the results may indicate vehicle consistency in respect of fuel efficiency per energy (not volume or mass), as shown in Figure 15.8. This quantity

may be used for analysing the fuel effect on changes in total powertrain efficiency or change in fuel related behaviour. All vehicle specific fuel consumption results turned out to be within +/- 1% of the average energy consumption with one exception: fuel 9 for vehicle A turned out with a 1.6 % reduction in energy consumption in relation to the average results. However, as the noise caused by fuel 9 was in line with the rest of the results, no precise reason for this phenomenon could be concluded, especially as the response of the other vehicles with corresponding fuel was the opposite (Figure 15.9). Overall, fuels 5 and 7 were found to have a tendency to increase the energy consumption for all vehicles by 0.5 to 1 %, meanwhile fuel 10 indicated a decrease in energy consumption by ca. 0.5 %, on average.

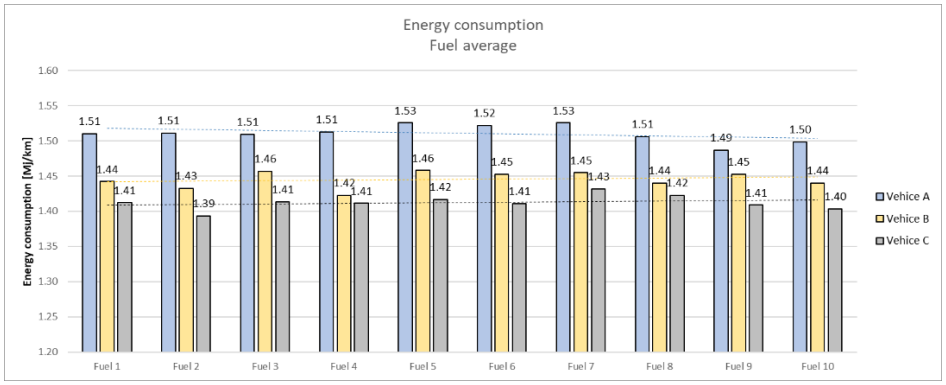


Figure 15.8 Average energy consumption per fuel and vehicle calculated from CO_2 emission factors

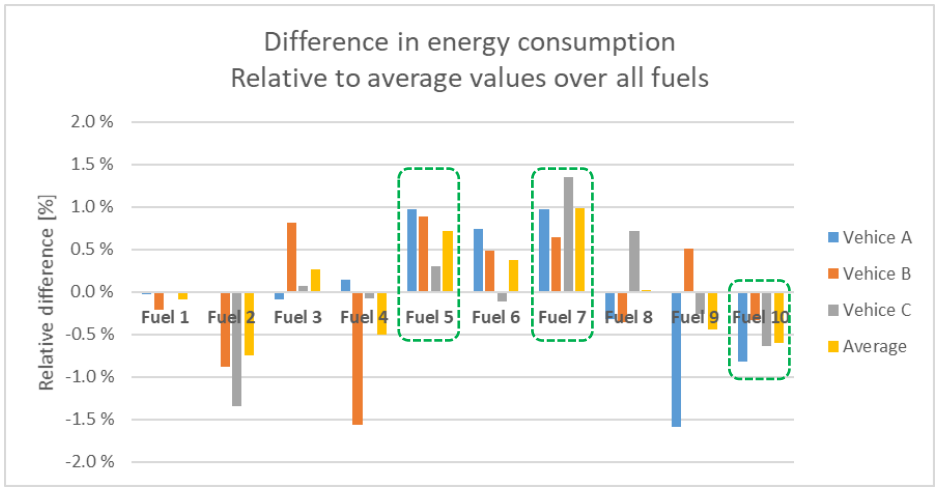


Figure 15.9 The relative change in energy consumption for all vehicles in relation to their corresponding average results

The response of other tail-pipe gaseous emissions, such as CO, NO_x and THC were equally studied using corresponding methods that were used for CO_2. The linear correlation between the emissions were typically found negligible, indicating that the fuel response may vary between vehicle to vehicle. “Best” linearity and highest R^2 was found for CO emissions, when comparing the results between vehicle B and C, with a R^2 of 0.231. However, it should be noted that the TP CO emissions for vehicle A were relatively stable, resulting in a virtually flat slope. As a conclusion of these gaseous EO results obtained, no clear correlation nor trend between fuel characteristics and gaseous emissions for any fuel/vehicle combination could be concluded. This indicate that the catalyst configuration and test-to-test

repeatability has higher significance than any specific fuel characteristics tested in this study. Due to the FTIR-related issues in this project (leading into device change in the middle of the experimental matrix), the TP NH_3 and N_2O analysis were emphasized less in terms of impact analysis, and thus the FTIR results were used more in this case for supervising purposes in case of any abnormal emission behavior throughout the tests could be found. Furthermore, due to the scope and nature of this study (focused on PN emissions), the gaseous emissions were seen more as secondary information, thus the effects caused by fuel properties were lesser studied in detail.

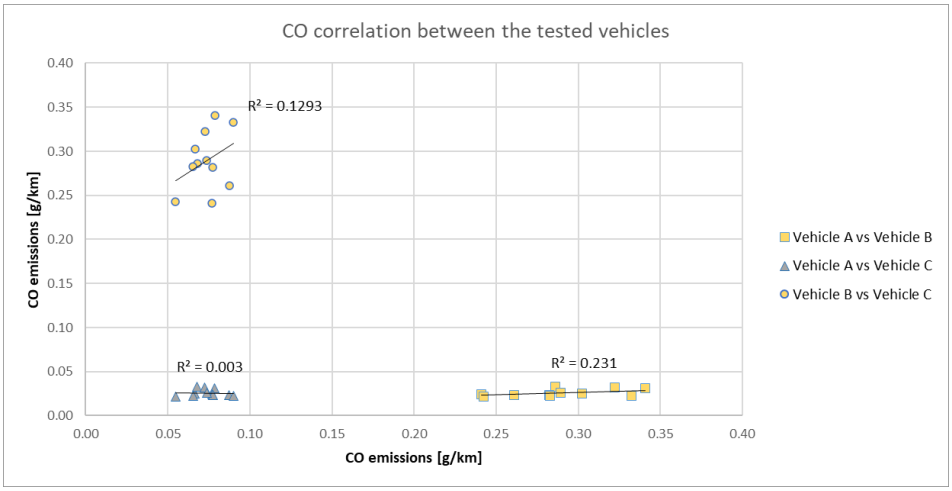


Figure 15.10 CO tailpipe emission response between vehicle to vehicle

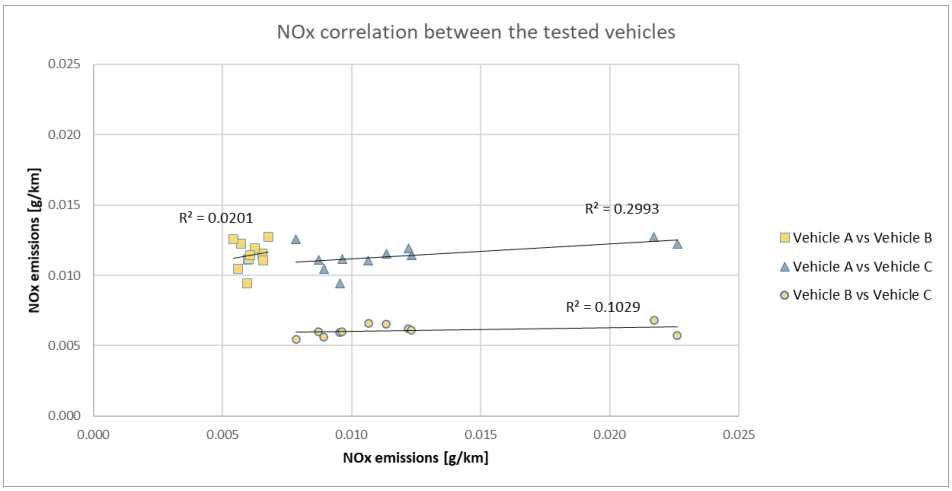


Figure 15.11 NO_x tailpipe emission response between vehicle to vehicle

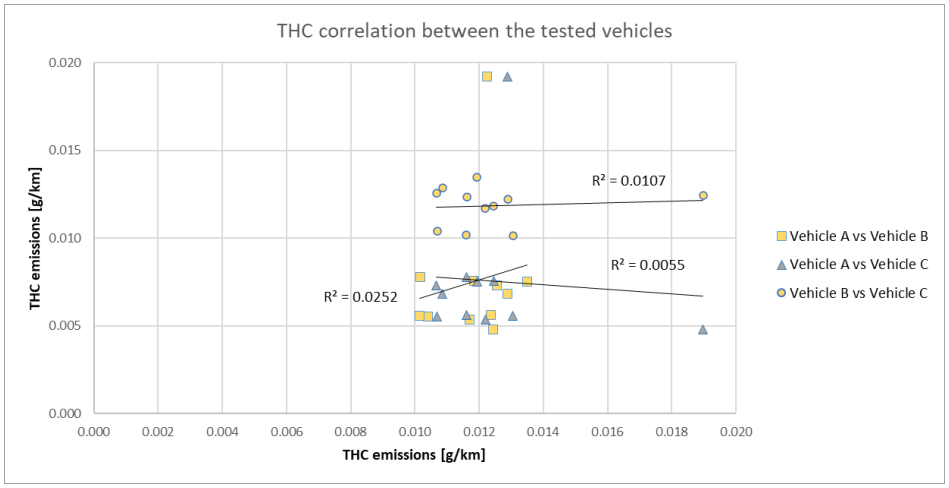


Figure 15.12 THC tailpipe emission response between vehicle to vehicle

15.1.3. Particulate emissions obtained from experimental studies

Exhaust particulate number (PN_{10} and PN_{23}) were sampled from both EO and TP using condensation particle counters (CPCs). The particulate emissions results were similarly treated as performed for the gaseous emissions. The focus of this study was mostly emphasised on PN emissions as the relation between particulate formation and fuel properties were most distinguishable and corresponding PN emissions could be found both for EO and TP emissions. Meanwhile the engine characteristics and fuel properties are generally the main elements influencing EO particulate emissions, TP emissions are additionally greatly dependent on the gasoline particulate filter characteristics. The conducted PN EO/TP measurements enabled analysis of both direct fuel effects on engine raw emissions and the effectiveness of used GPF technologies.

For each vehicle/fuel combination, PN emissions were expressed as the average results from the successful (non-discarded) tests. The deviation of the PN emissions were treated as standard deviation, expressing non-fuel related noise, i.e. was considered as pure error. The error bars shown in each figure represent the confidence interval caused by pure noise.

The initial impression seen from the results was that the vehicles tend to produce relatively different quantities of PN emissions both in terms of EO and TP as shown in ***Table 15.1***. The overall tendency found was that GDI engines used in these tests (Vehicle A & B) seem to produce greater shares of sub PN_{23} EO (PN_{10} to PN_{23}) emissions compared to the PFI engine (Vehicle C). However, the PN_{23} EO tendency was less conclusive as the PN_{23} EO emissions for Vehicle A were found even lower than for Vehicle C; but Vehicle B, contributed with distinctly highest PN_{23} EO results. Furthermore, remarkable differences the GPF efficiency and PN TP emission were noted between the test vehicles. Despite contributing with highest PN_{10} EO emissions, lowest PN TP emissions, and therefore highest reduction of particulate emissions over the GPF was found highest for vehicle A. The reduction efficiency was in this case ca. 99.9 % for PN_{10} and 99.6 % for PN_{23}. Correspondingly, poorest GPF performance and highest PN TP emission were recorded for vehicle B. Note that, GPF filtration efficiencies are only indicative as particle losses in the measurement system were not necessarily equal for EO and TP sampling due to different lengths of sampling lines and different type of diluters used. However, as

the measurement system was similar for all vehicles and fuels, results can be compared between vehicles or fuels.

The particle mass (PM) was sampled for each of the four test phases. The method only gives a single mass value over a phase and this method doesn't produce any real time results. All vehicles produced very small PM results as shown in ***Table 15.1*** and the total average of all PM results was ~3% of the limit for Euro 6 emission class. The Vehicle B did produce somewhat higher PM results than the other two. Vehicle C was the only PFI engine vehicle of the group, but vehicle A was still almost as good. Vehicle B's filter samples were the only ones that had visible soot on them.

However, the PM results were too low to produce enough accurate results for a comparison. No significant differences in PM emissions were found. The main reason for this was suspected to be caused by the ultra-low PM emissions, and the GPFs tend generally to reduce PM in SI engines close to any reasonable detection limit.

Table 15.1 The average magnitude of particulate emissions per test vehicle

Emission type	Average magnitude	Vehicle A	Vehicle B	Vehicle C
PN10 EO	**[1*10^11/km]**	63.0	45.4	18.4
PN23 EO	**[1*10^11/km]**	3.6	13.9	4.4
PN10 TP	**[1*10^11/km]**	0.04	0.87	0.1
PN23 TP	**[1*10^11/km]**	0.01	0.83	0.1
PN23 reduction over GPF	**%**	99.9 %	98.1 %	99.5 %
PN10 reduction over GPF	**%**	99.6 %	94.0 %	98.5 %
PM	**mg/km**	0.12	0.13	0.12

Furthermore, the overall relationship between fuel response and PN behaviour from vehicle to vehicle was seen less consistent than expected, and the fuel related PN trends were found somewhat vehicle specific. As an example, the contribution of noise (or pure error, standard deviation) was not found consistent for all vehicles throughout the tests. This means that the noise contribution between fuel to fuel was found greater for certain fuels than others. However, the fuels contributing to highest pure error was not found uniform between fuels, therefore it was already in an early phase suspected to be caused by other elements than fuel related variables. The initial PN emissions acquired for each vehicle are shown in ***Figure 15.13***, ***Figure 15.14***, ***Figure 15.15***, ***Figure 15.16***, ***Figure 15.17***, ***Figure 15.18***, ***Figure 15.19***, ***Figure 15.20*** and ***Figure 15.21***.

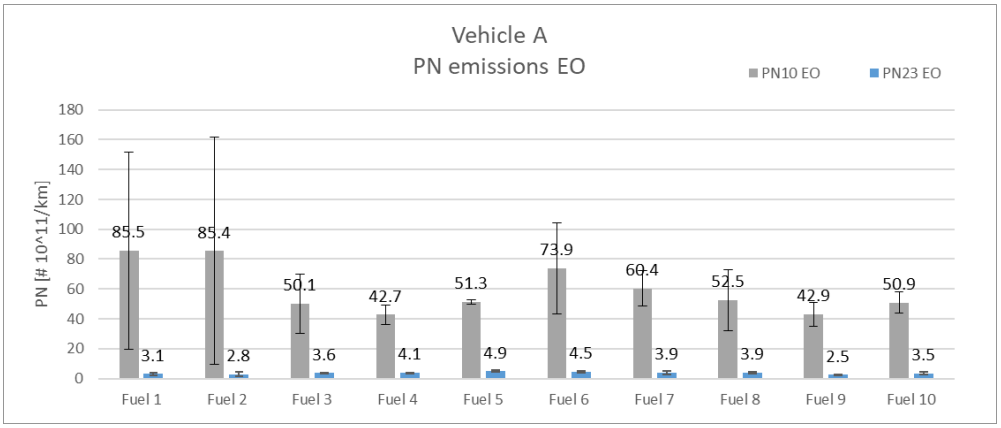


Figure 15.13 Average PN_{10} and PN_{23} EO emissions acquired from vehicle A

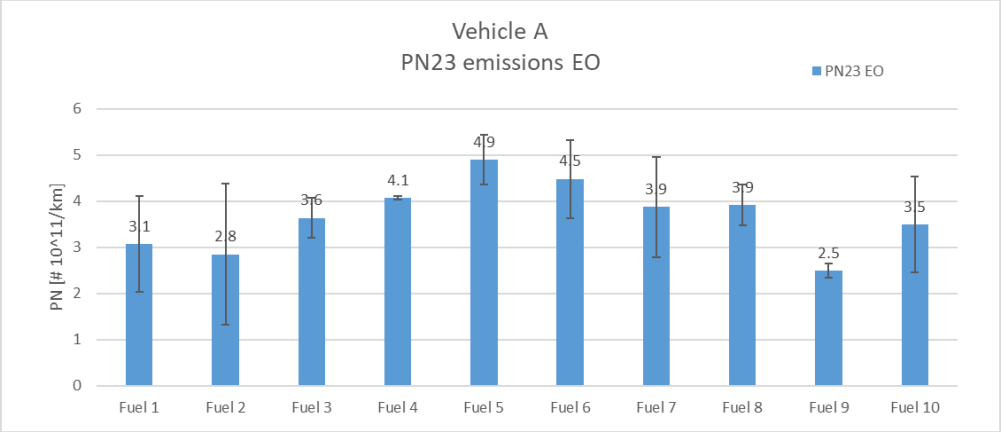


Figure 15.14 Average PN_{23} EO emissions acquired from vehicle A

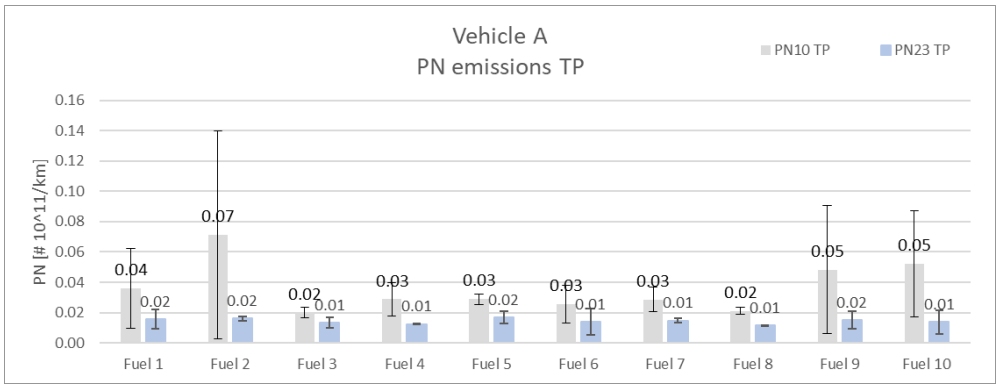


Figure 15.15 Average PN_{10} and PN_{23} TP emissions acquired from vehicle A

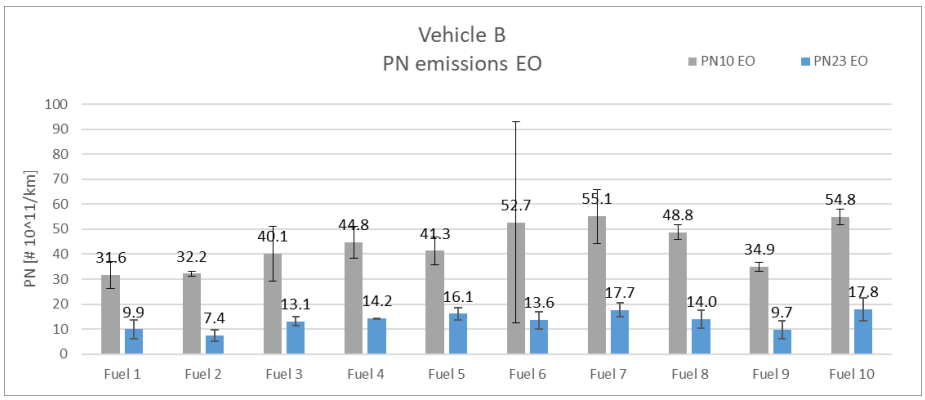


Figure 15.16 Average PN_{10} and PN_{23} EO emissions acquired from vehicle B

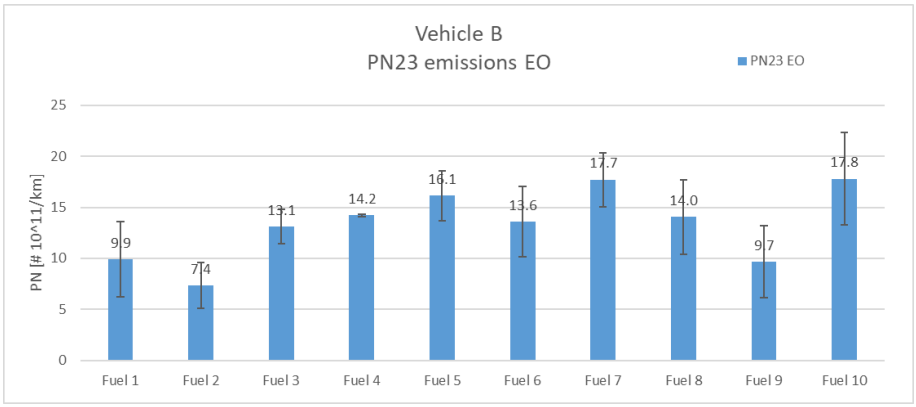


Figure 15.17 Average PN_{23} EO emissions acquired from vehicle B

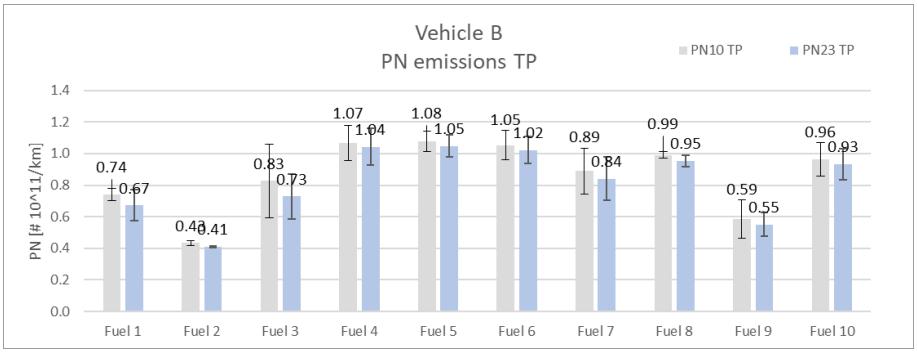


Figure 15.18 Average PN_{10} and PN_{23} TP emissions acquired from vehicle B

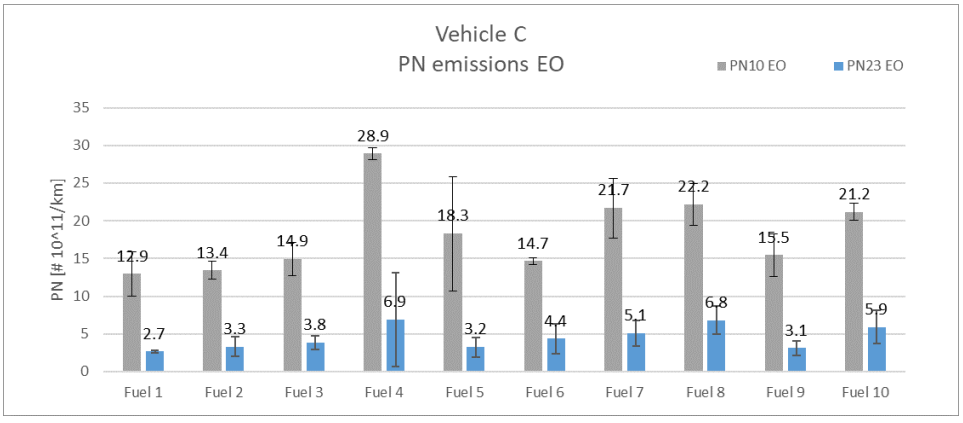


Figure 15.19 Average PN_{10} and PN_{23} EO emissions acquired from vehicle C

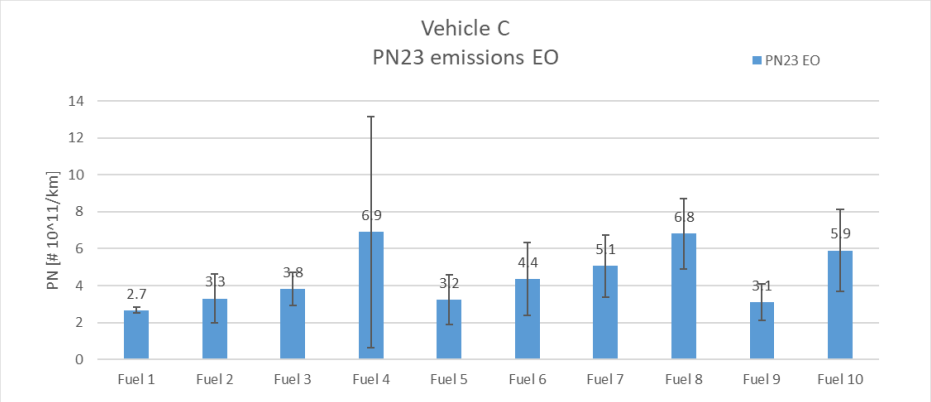


Figure 15.20 Average PN_{23} EO emissions acquired from vehicle C

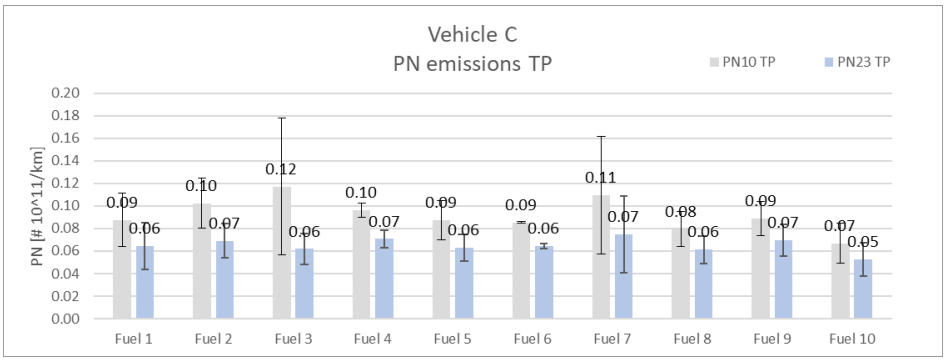


Figure 15.21 Average PN_{10} and PN_{23} TP emissions acquired from vehicle C

The vehicle-to-vehicle PN results were compared by determining the linear correlation between the test vehicles. The response on change in fuel properties for all three vehicle combinations (A vs B, A vs C, B vs C) are plotted in corresponding figures shown for PN_{10} EO in ***Figure 15.22***, for PN_{23} EO in ***Figure 15.23***, for PN_{10} TP in ***Figure 15.24*** and for PN_{23} in ***Figure 15-25***.

The results indicate that the fuel response for PN_{10} EO are relatively different for each vehicle. The correlation of fuel response between vehicle to vehicle was found "highest" for the EO PN emissions. Interestingly, PN_{10} EO emissions between vehicle A & C were somewhat contradictory as the trend was opposite to a consistent behavior. Additionally, the spread of PN EO indicate that the direct fuel effect is not totally consistent between vehicle to vehicle. As the PN TP emissions are highly reliant on the vehicle GPF, the correlation between the test vehicle PN TP emissions were less significant than for the PN EO trends. Based on the results acquired in these tests no significant relation between PN TP emissions between the test vehicles were distinguished. One fundamental problem suspected influencing the comparison was the variation in fuel specific pure error, which was found not consistent between vehicle to vehicle.

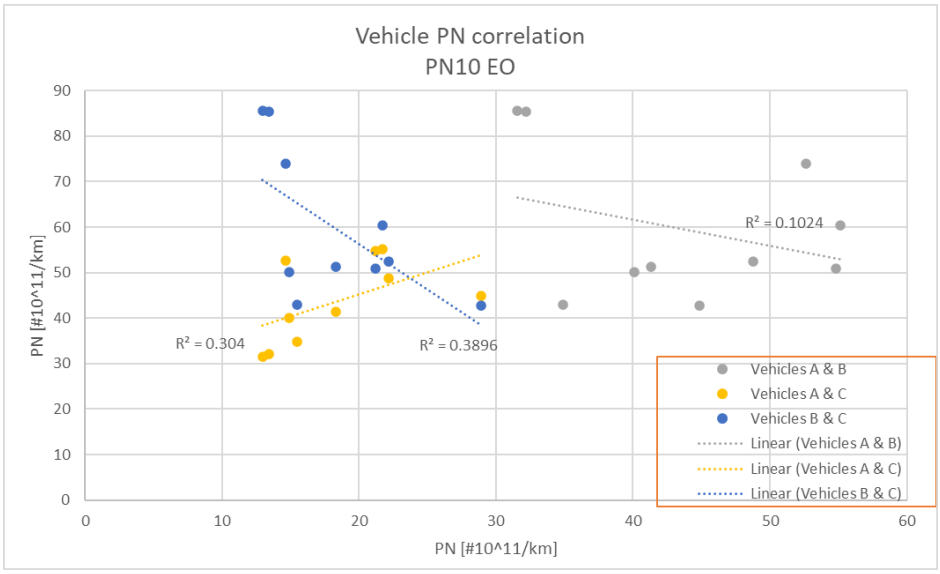


Figure 15.22 Correlation between the different vehicle PN_{10} EO emissions

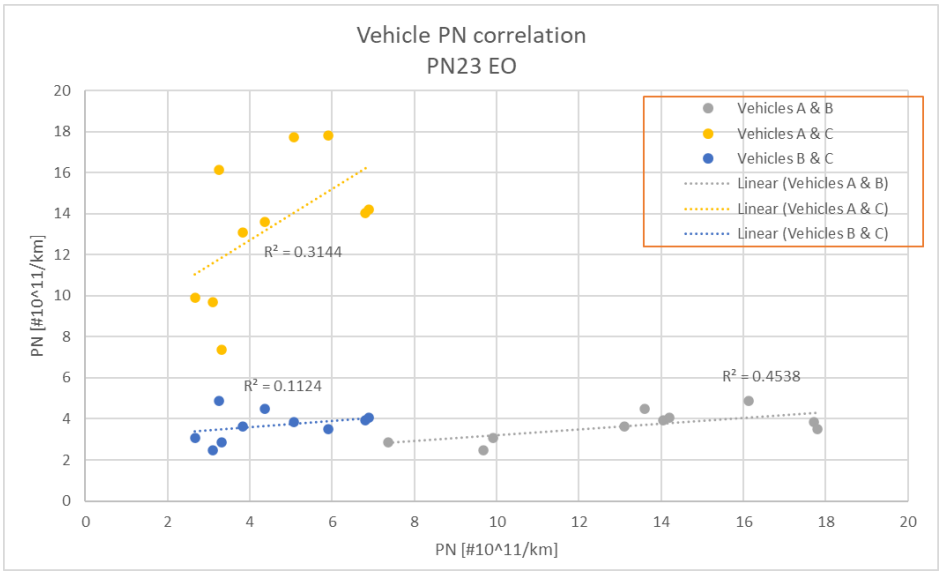


Figure 15.23 Correlation between the different vehicle PN_{23} EO emissions

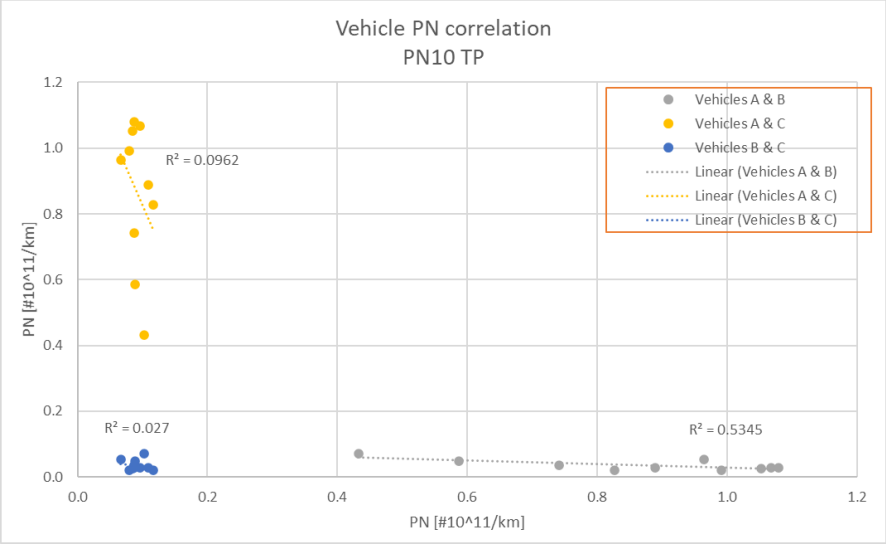


Figure 15.24 Correlation between the different vehicle PN_{10} TP emissions

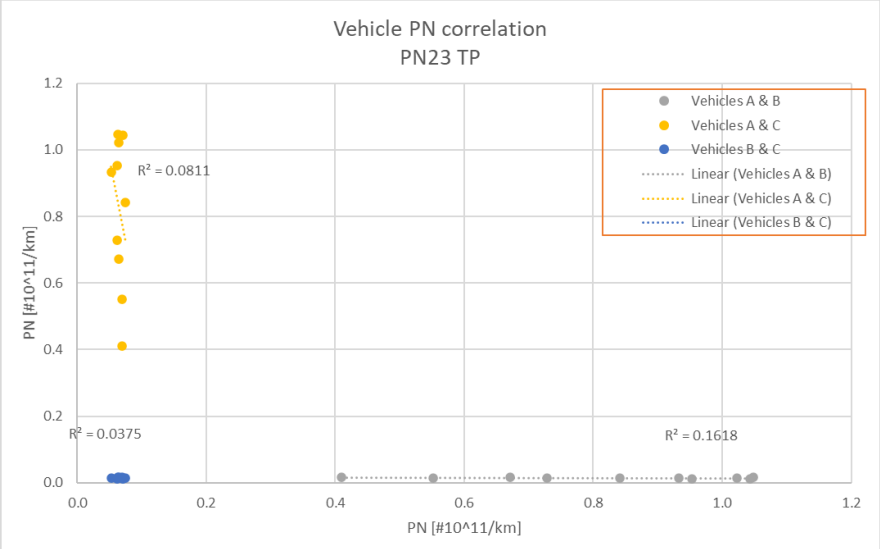


Figure 15-25 Correlation between the different vehicle PN_{23} TP emissions

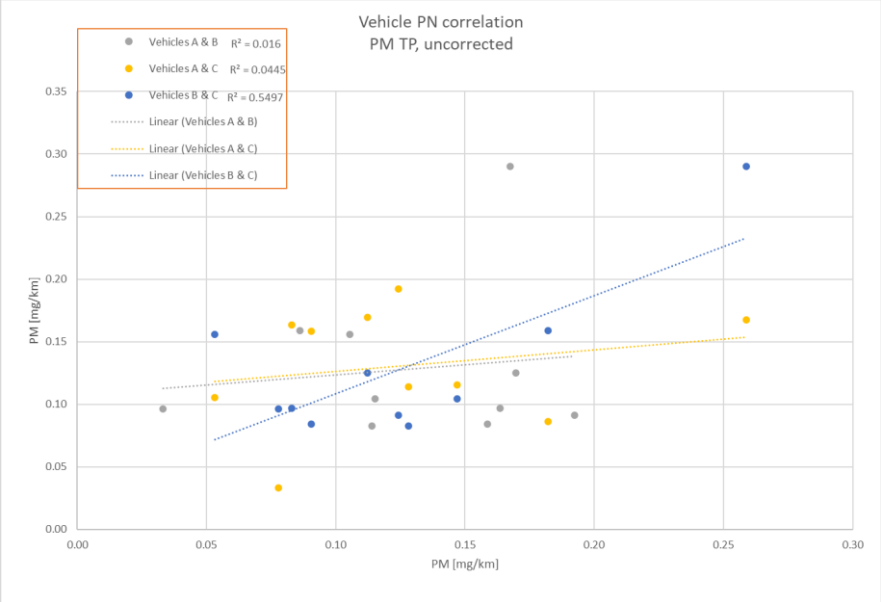


Figure 15.26 Correlation between the different vehicle PM TP emissions

The ELPI measured particles after dilution with DEED and in parallel with PN10 and PN23 TP CPCs. Due to the low TP emissions and dilution with DEED, particle concentrations were very low at inlets of the instruments, especially for A and C vehicles. Due to low particle concentrations, size measurement of the ELPI was not reliable. Most of the time ELPI measurement signals were essentially noise, except the startup peak and some peaks from vehicle B. Figures 4.27, 4.28 and 4.29 illustrate low particle concentrations by showing PN10 TP instrument reading and ELPI raw signals for stages 1-4 (7 – 165 nm). To achieve reliable long-term data from the ELPI, measured current should be well above 10 fA and contain distinct emissions peaks. An attempt was made to calculate mean diameters from the particle size distribution, but as the actual measurement signals were very low, both size distributions and mean diameters proved out to be uncertain and were therefore not compared in this report.

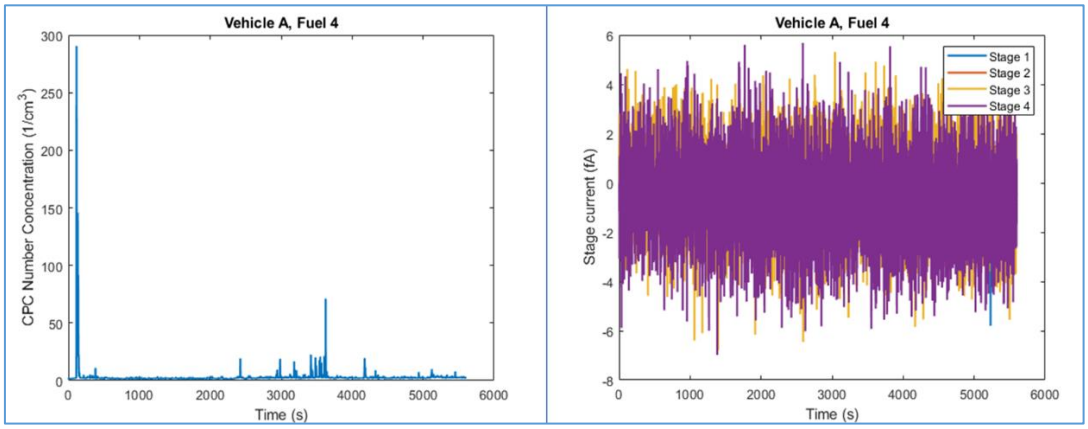


Figure 15.27 PN10 TP CPC and ELPI signal for fuel 4 and vehicle A

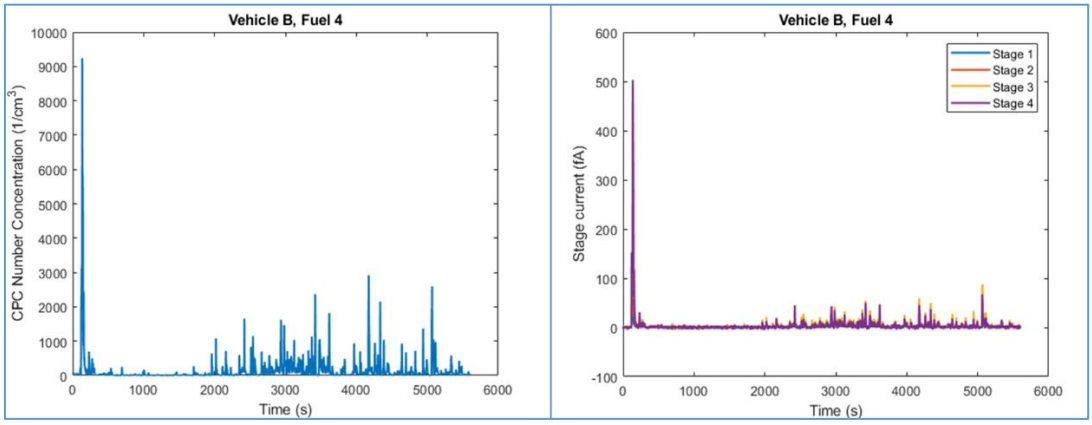


Figure 15.28 PN10 TP CPC and ELPI signal for fuel 4 and vehicle B

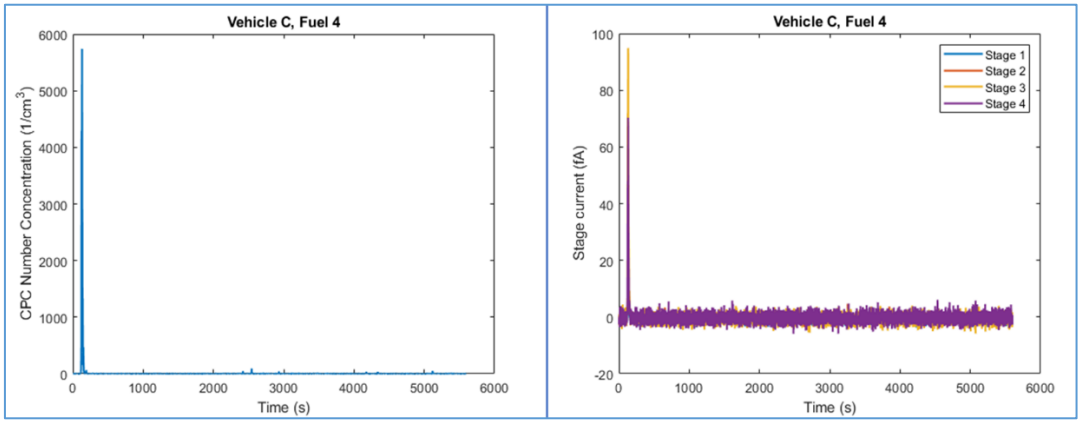


Figure 15.29 PN10 TP CPC and ELPI signal for fuel 4 and vehicle C

15.2. DATA TRENDS AND DATA CORRECTION

15.2.1. An overview of PN trends

To distinguish the relation between real fuel effect on PN behaviour and measurement uncertainties, the contribution of other non-fuel related effect needs to be considered in the analysis. The major factors causing potential uncertainty are either vehicle related behaviour (natural variation of repeatability) or other sources causing measurement noise, referred as pure error. One major contributor for a bias in vehicle testing may be trends caused by vehicle, engine and transmission settling. To study the contribution of these factors, the trends of the emission results were evaluated for further need of data correction. This was performed by gathering all calculated emissions per vehicle in a chronological test order. A trendline for each PN trend was fitted and the slope for the trends were examined. Because the test matrix and fuel test order were designed for the purpose of maximizing the results stability, the slope of the trendline should, in a case where no errors or settling occur, be close to zero. This was however not the case for any vehicle tested in this study. Descending trends were found for all PN emission with vehicle A (***Figure 15.30***). Particularly, the slope of the PN_{10} EO emission trend was found strong, with exceptionally high PN emissions for the first 8 tests. After the first 8 tests, the trend for PN_{10} EO emission settled milder. Overall,

the PN emissions for Vehicle B was generally most stable with least effect of any trend change (***Figure 15.31***). For vehicle C, the PN_{10} EO emissions were found more consistent than PN TP (***Figure 15.32***). Interestingly, the trend for PN_{23} EO emissions were somewhat increasing throughout the tests. Despite the PN EO behaviour, both vehicle A's and C's PN TP emissions (PN10 and PN23) were evenly reducing throughout the test campaign, indicating that some soot off-loading still may have occurred. The results generally indicated that the PN emissions did suffer from some non-fuel related trends. As a result of the findings, it was suggested that trend corrections would be advisable for reducing any excessive uncertainties when studying any fuel properties related effects.

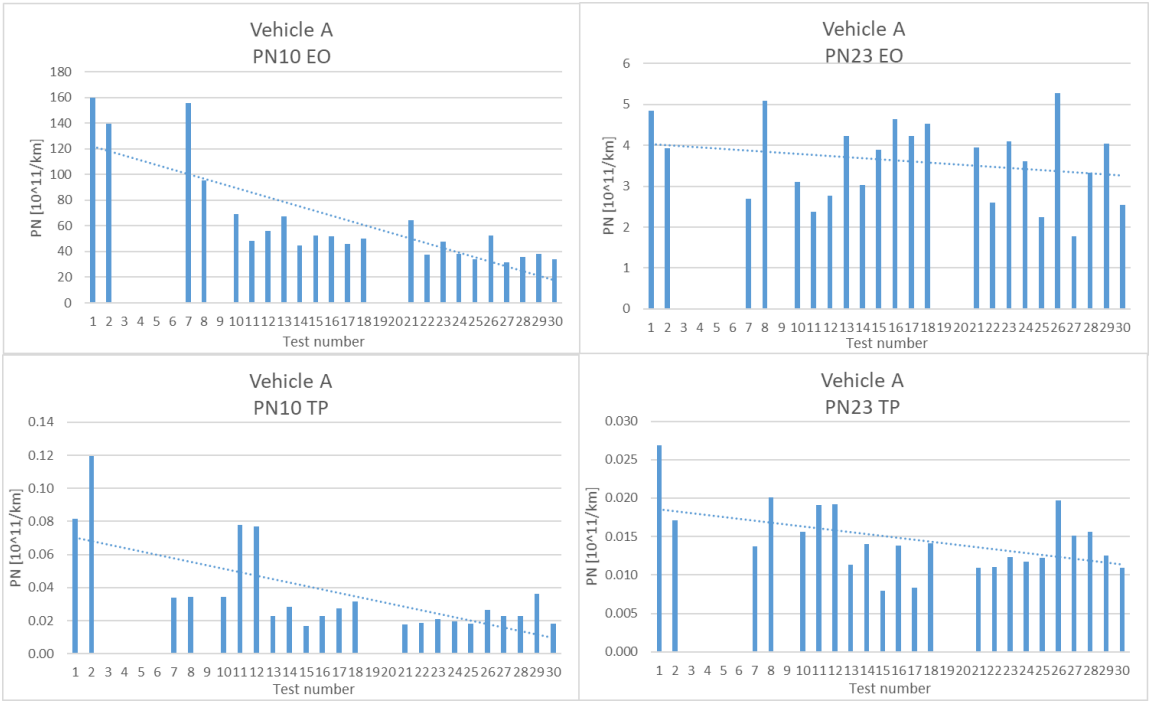


Figure 15.30 PN trends for Vehicle A

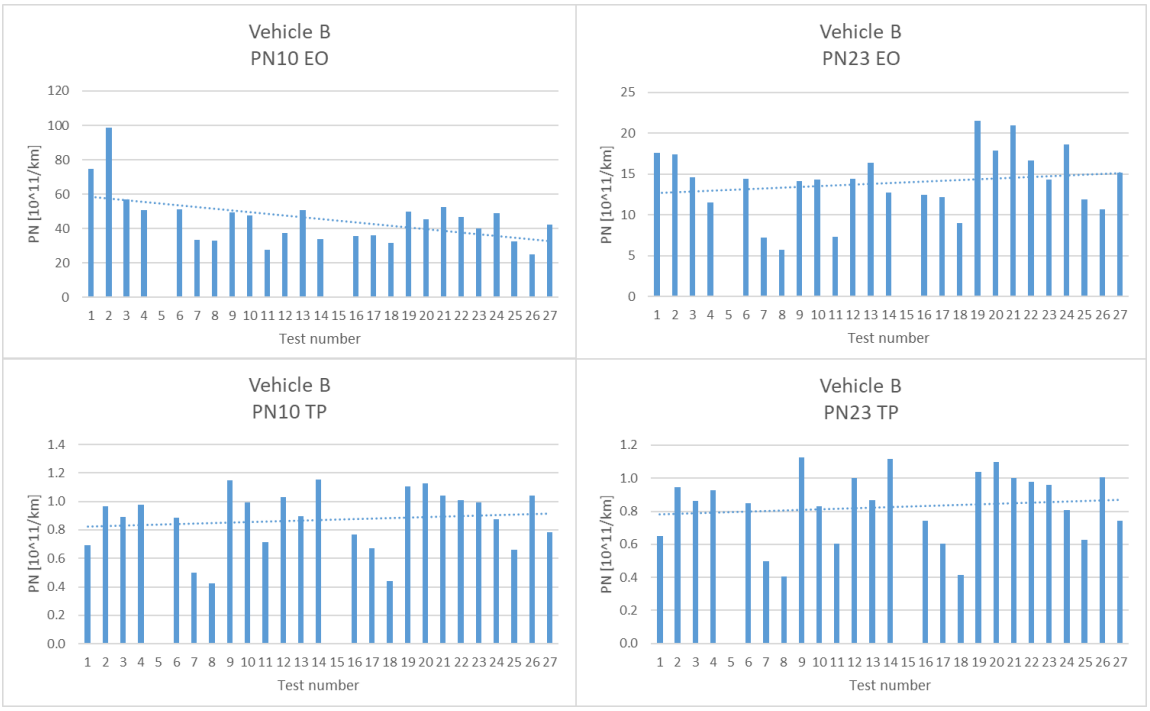


Figure 15.31 PN trends for Vehicle B

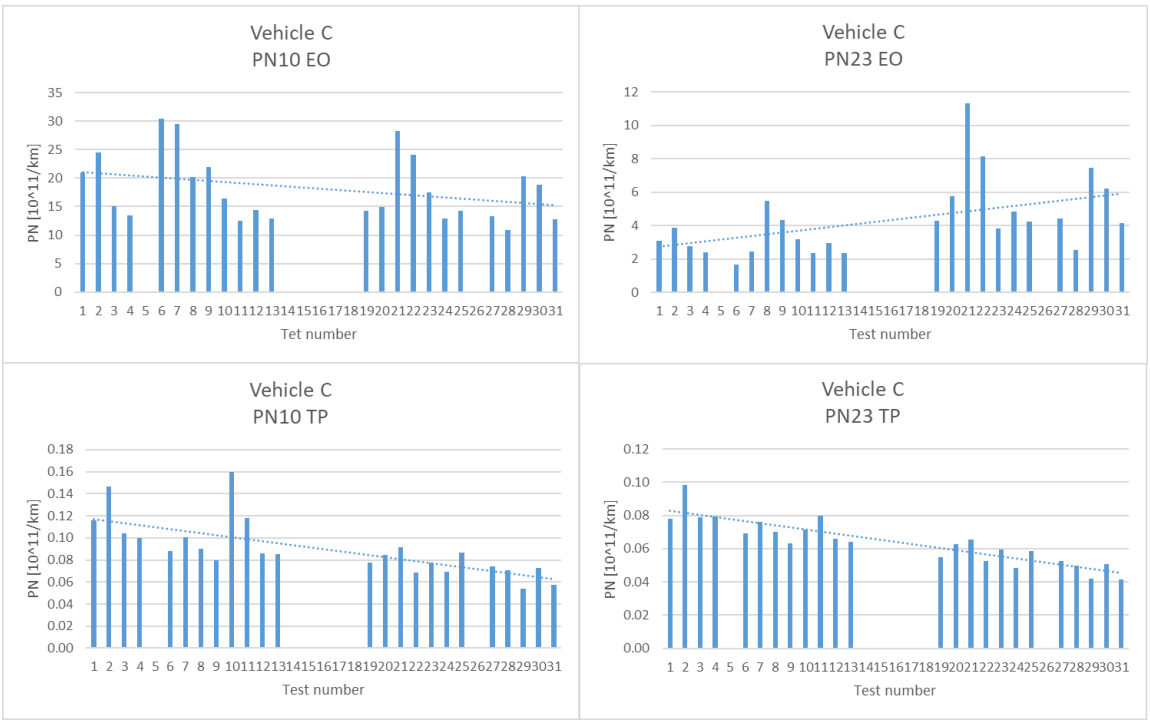


Figure 15.32 PN trends for Vehicle C

15.2.2. Data corrections

As clear trends in PN behaviour were found, suitable correction measures were studied for reducing any time-based data bias. To address this problem, the data set for each emission component was fitted in Microsoft Excel software with a linear and a non-linear (second degree polynomial) trendline depending on which method was concluded to produce the highest value of the coefficient of determination (R^2). When producing the trendline, the order number of the discarded tests was considered but any discarded values were considered as blank values. An example of the fitting for Vehicle A PN_{10} EO is shown in ***Figure 15.33***. After finding the best fit, a correction factor was created for each data point according to the chronological order. The correction factor was calculated by proportioning the mean value obtained from all tests (except the discarded) data with the expected value obtained from the regression model. This correction method include data from all test fuels, thus neglecting the effect of fuel differences. The correction was performed for all test results considering PN emissions, RDE (whole test), Phase 1 and the steady state conditions.

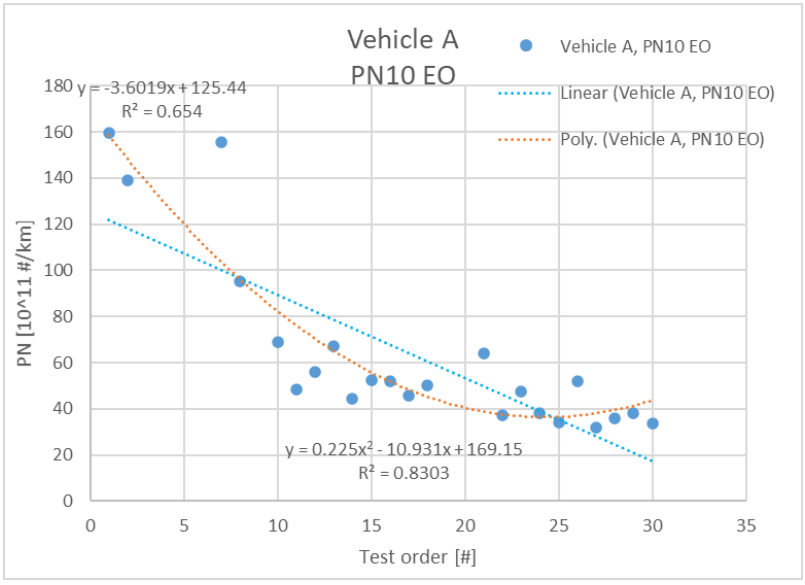


Figure 15.33 Fitting of a linear and a polynomial trend for Vehicle A PN_{10} EO emissions

The fitment of the trends as non-linear is justified in cases where the linear trend is evidently not correlating sufficiently with a non-linear trend such as in this example. In such cases, a linear correction would cause a bias in the corrected data, causing an e.g. downwards sloping trend to be corrected insufficiently or excessively either in the early part or in the late part of the data set. An example of the correction effect both with a linear and a non-linear correction is shown in ***Figure 15.34***. As the data is more strongly affected in the early part of the test, the linear correction is sensitive for under-correcting the early PN tests, correspondingly overcorrecting the later PN values. Furthermore, less significant drawbacks occur with a non-linear correction even for linear trends if the changes in vehicle behaviour is consistent and no disrupting errors in the test nor test vehicle take place.

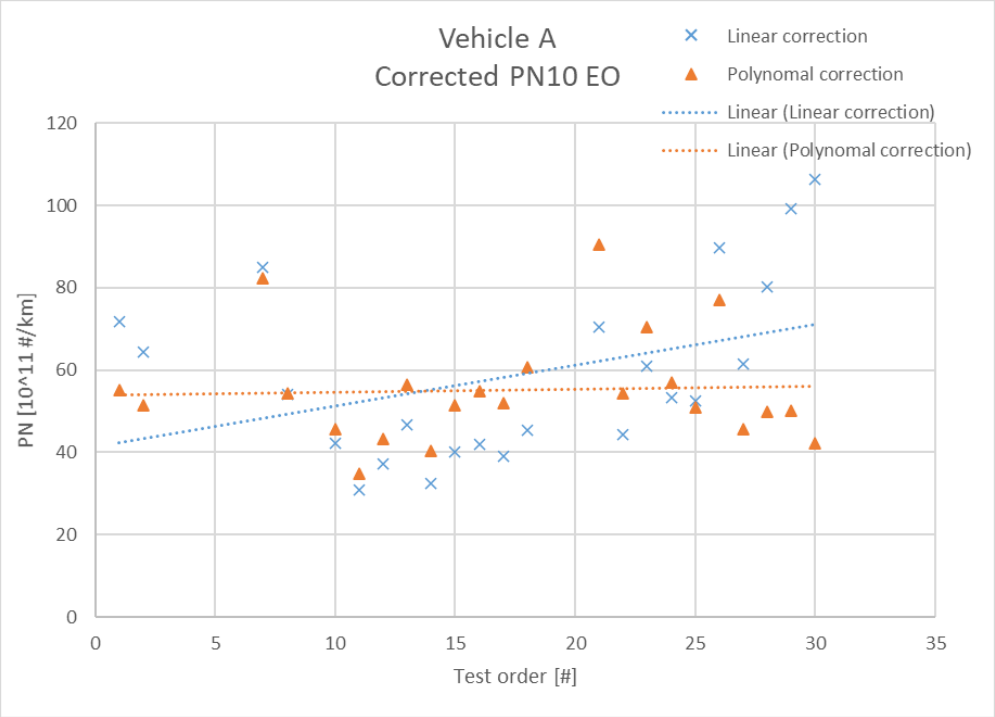


Figure 15.34 The effect of linear and polynomial correction of PN emissions

The outcome of a non-linear correction in relation to the uncorrected PN data is shown as an example in ***Figure 15.35***. The non-linear correction results in a data set, where the trend line is virtually horizontal, and the turning point is in the middle of the data set. Therefore, both data before and after the turning point is corrected, but with a magnitude in proportion to the trend change.

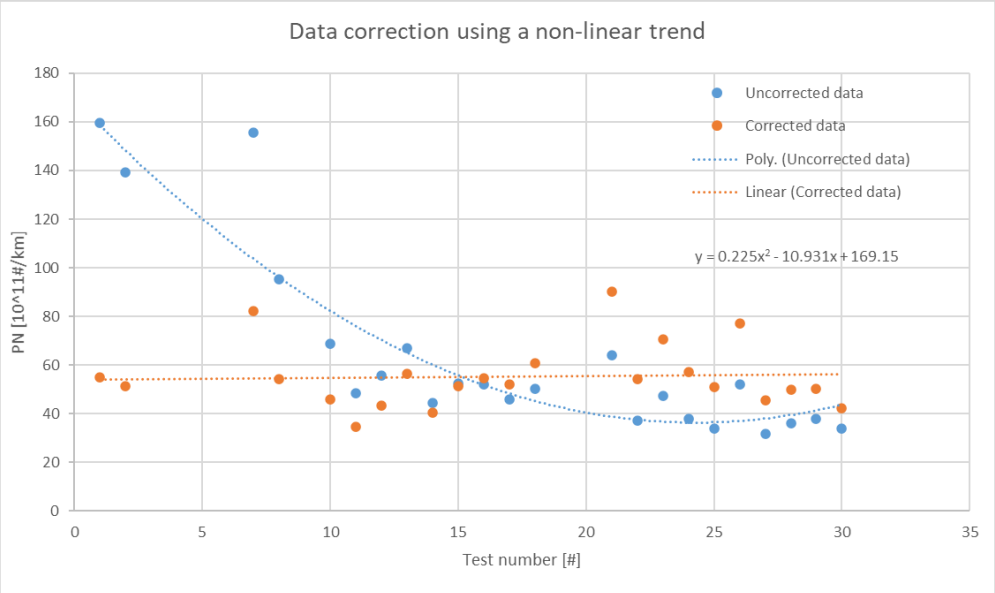


Figure 15.35 An example of data after a non-linear correction

The effect of the different correction types (linear for and non-linear correction) on coefficient of determination are illustrated for vehicle A in Figure 15.36, for

vehicle B in Figure 15.37 and for vehicle C in Figure 15.38. For vehicle A and B, the non-linear fitment is generally significantly improving the coefficient of determination compared to a linear fitment in all cases. For vehicle C the effect of correction was typically similar for both types of correction. This indicates that the PN trend behaviors for the GDI vehicles (Vehicles A & B) were far less linear than for the PFI case (Vehicle C).

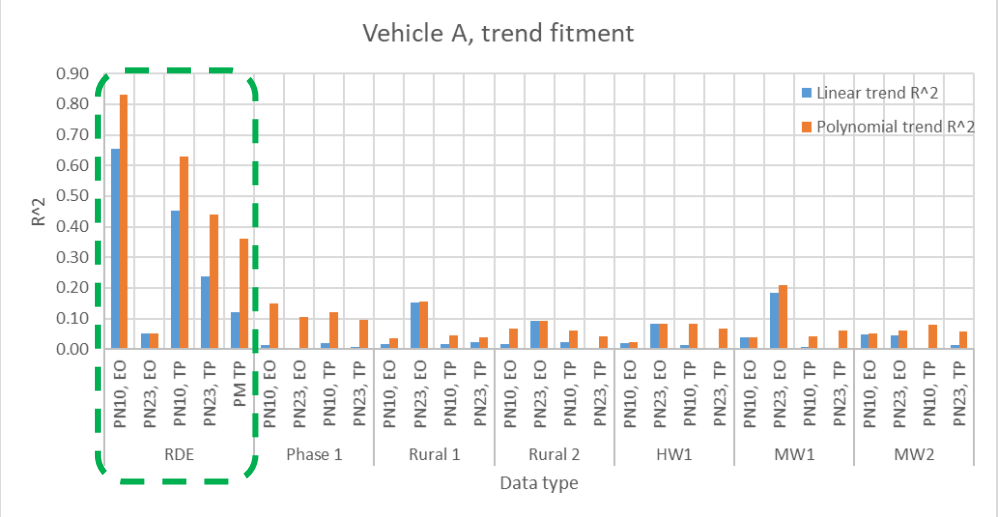


Figure 15.36 The R^2 values of the linear and non-linear trend fitting for vehicle A

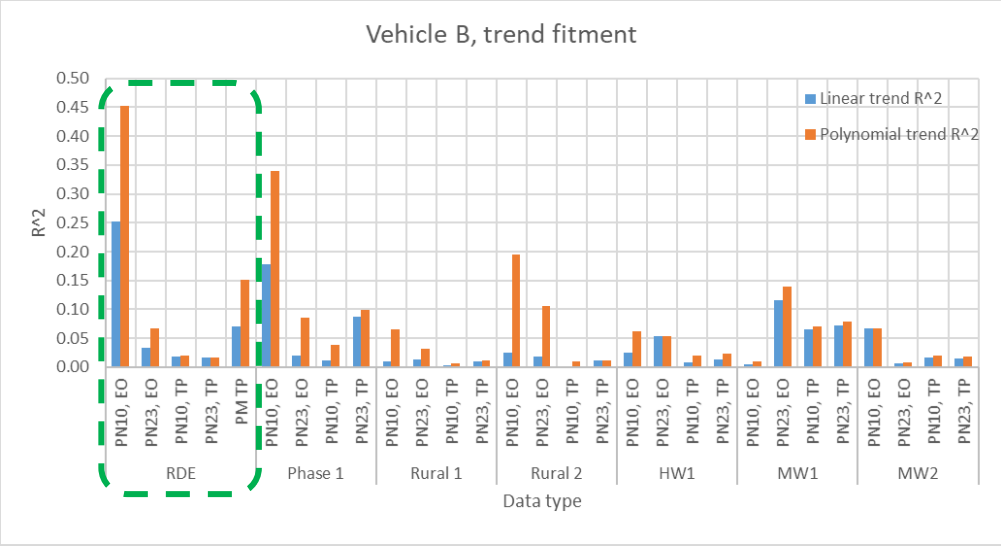


Figure 15.37 The R^2 value of the linear and non-linear trend fitting for vehicle B

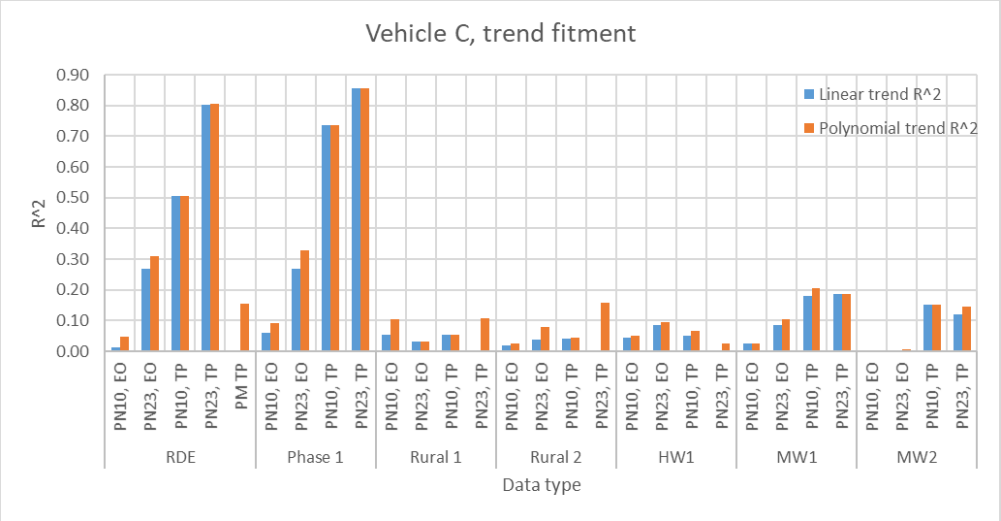


Figure 15.38 The R^2 value of the linear and non-linear trend fitting for vehicle C

15.3. PN EMISSIONS AFTER CORRECTION

Table 15.2 shows the vehicle specific average deviation in PN emissions over the complete test before and after data correction. The average deviation was calculated as an average value from the individual deviation for each fuel. For vehicles A and C the correction distinctly decreased the deviations for the results for each fuel. Typically, most of the improvements were achieved for those data sets that were most affected by descending PN trends. This was however not the case for vehicle B, as the trends were concluded less significant and typically stable.

Table 15.2 Average standard deviation for PN emissions before and after correction

		PN10EO	PN23EO	PN10TP	PN23TP	Average
Vehicle A	Uncorr	36 %	21 %	48 %	27 %	33 %
Vehicle A	**Corr**	**18 %**	**19 %**	**36 %**	**21 %**	**24 %**
Vehicle B	Uncorr	19 %	22 %	11 %	11 %	16 %
Vehicle B	**Corr**	**24 %**	**23 %**	**10 %**	**10 %**	**17 %**
Vehicle C	Uncorr	15 %	38 %	24 %	22 %	25 %
Vehicle C	**Corr**	**14 %**	**27 %**	**9 %**	**4 %**	**13 %**

Figure 15.39 shows the PN results for Vehicle A with their corresponding deviations before and after correction. Greatest reduction in the deviation was obtained for those fuels with most deviation to begin with. Most of the time, the correction did not significantly affect the average fuel specific PN result. However, for the case of PN10 (EO and TP) for vehicle A, the correction did not affect only the deviation alone, but also influenced the average fuel specific PN result.

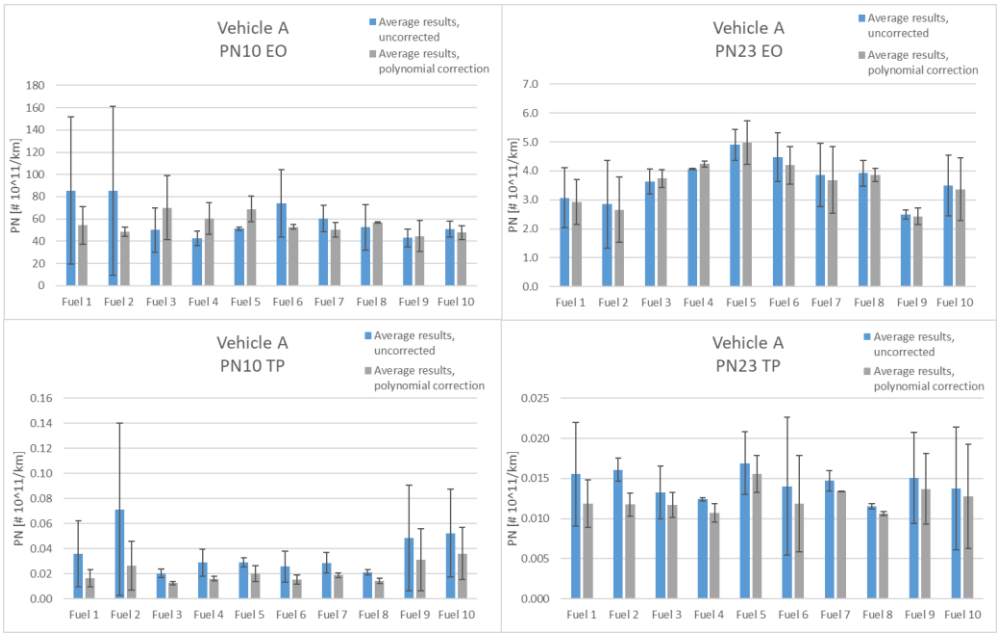


Figure 15.39 A comparison of the PN results for Vehicle A before and after data correction

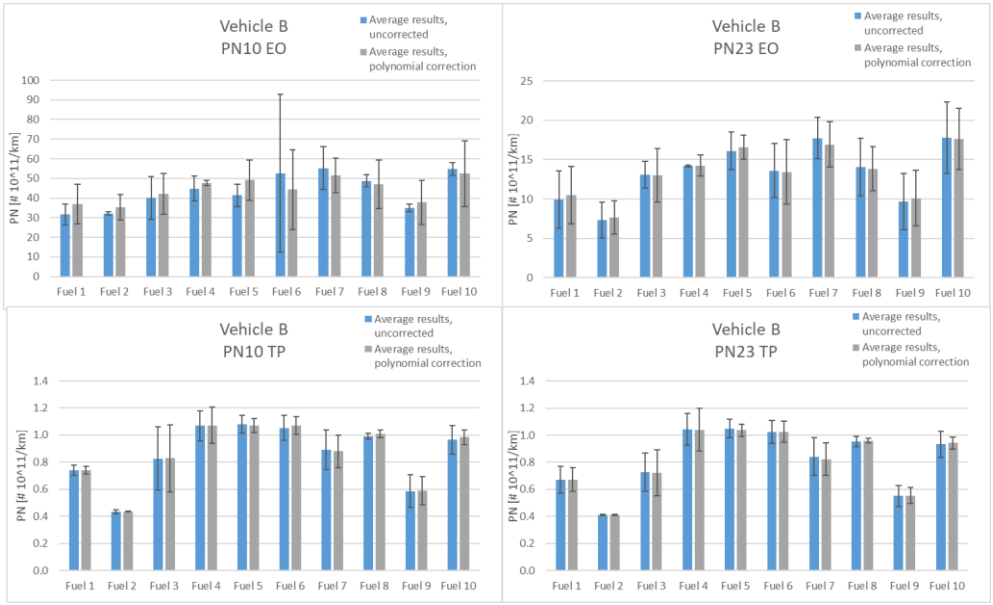


Figure 15.40 A comparison of the PN results for Vehicle B before and after data correction

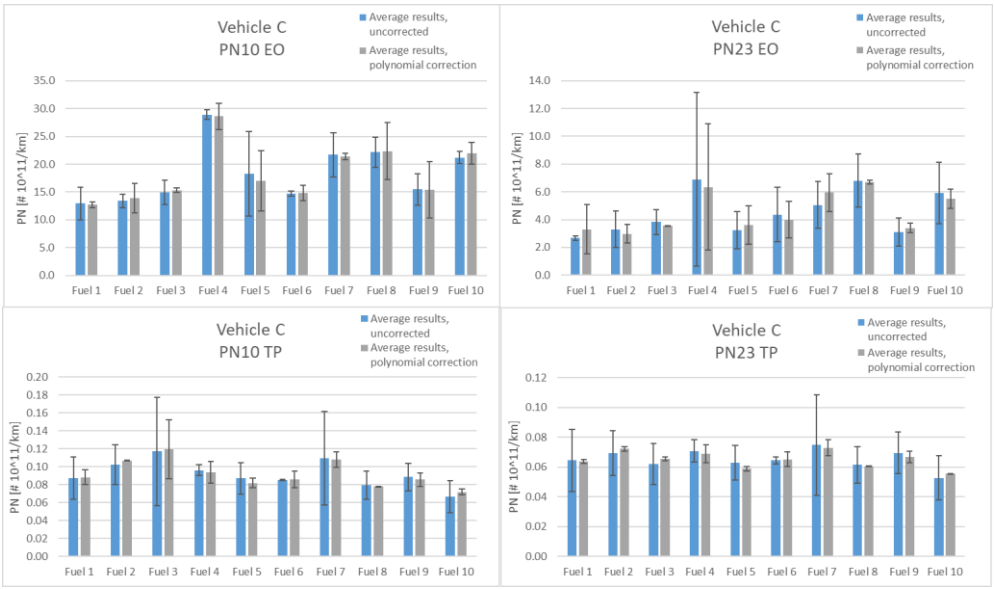


Figure 15.41 A comparison of the PN results for Vehicle C before and after data correction

15.4. ASSESMENT OF RELATIONS BETWEEN PN EMISSIONS

After the data correction, the PN data was further analyzed for studying any possible relations between PN10 and PN23 emissions. Likewise, a similar study between EO and TP was performed. ***Figure 15.42*** shows the average PN emissions per vehicle. The ratio between PN_{10} and PN_{23} emissions was found higher for all EO emissions compared to TP emissions. This effect was especially significant for vehicle A, whose PN_{10} EO emissions were ca. 15.4. times higher than the PN_{23} emissions. The corresponding ratio was for vehicle B 3.3 and for vehicle C 3.9. The GPFs seem, however, to reduce particulates very efficiently, especially for PN emissions between 10 and 23 nm, as the difference between PN_{10} and PN_{23} TP emissions were found very small. The results obtained in this study suggests therefore that the PN emission performance for modern vehicles equipped with GPF is excellent and that the current technologies are well prepared even for future legislative changes, e.g. the moving from the current PN_{23} limit to a new PN_{10} threshold.

The presence of GPFs also affects how well the PN emissions correlate between EO and TP PN. The response between PN EO and TP was found to be unequal from vehicle to vehicle. For vehicles A and C, correlation between EO and TP was found relatively low as shown in ***Figure 15.43***: in ***Figure 15.44***, meanwhile a relatively clear connection between the respective PN emissions could be distinguished. Due to the filtration characteristics of the GPFs, the correlation between PN10 and PN23 emissions was typically more evident for EO emissions than for TP as seen in Figure 15.45 and Figure 15.46. The PN behavior between PN10 and PN23 was found most uniform for vehicle B, and the linear correlation for both (PN10 and PN23) EO and TP emissions were above 0.95. The GPF seems to reduce the correlation between PN characteristics between EO and TP PN emissions for vehicles A and C, as the R^2 value between PN_{10} and PN_{23} emissions reduces over the GPF. This yet again suggests that the filtration efficiency is rather dependent of particulate size and not solely on particulate concentration. Additionally, the results clearly show that the characteristics between GPFs depending on vehicle brand may vary from case to case.

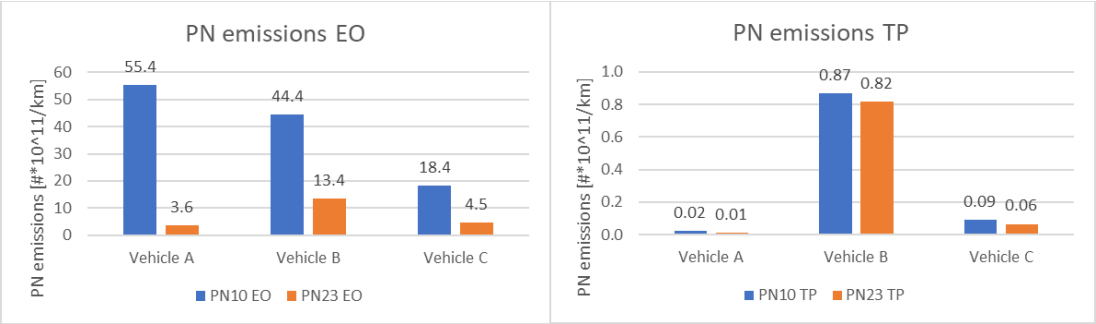


Figure 15.42 Average PN10 and PN23 emissions per vehicle, EO and TP (corrected)

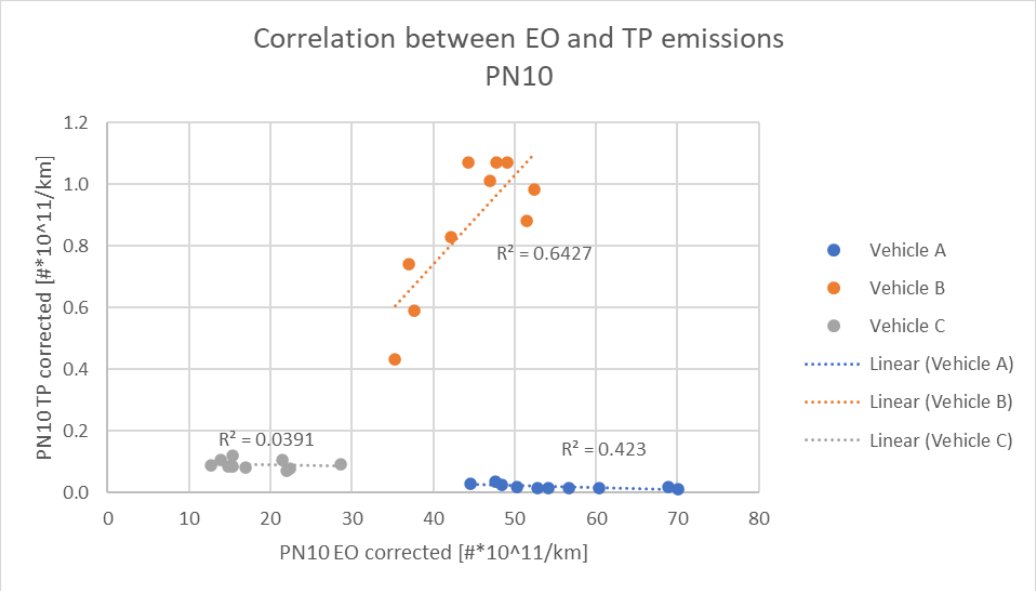


Figure 15.43 Correlation between PN10 EO and PN10 TP emissions

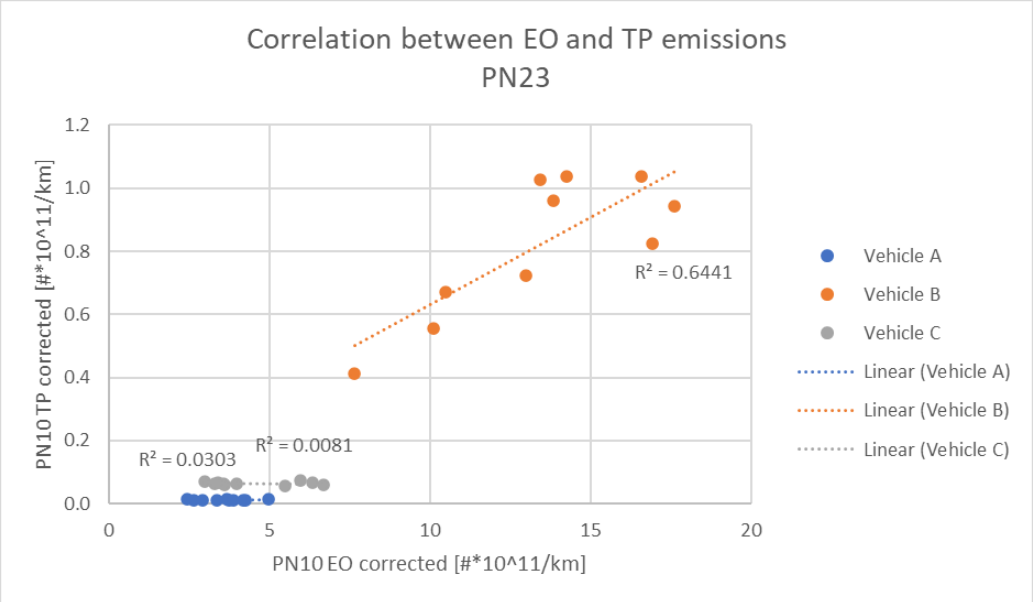


Figure 15.44 Correlation between PN23 EO and PN23 TP emissions

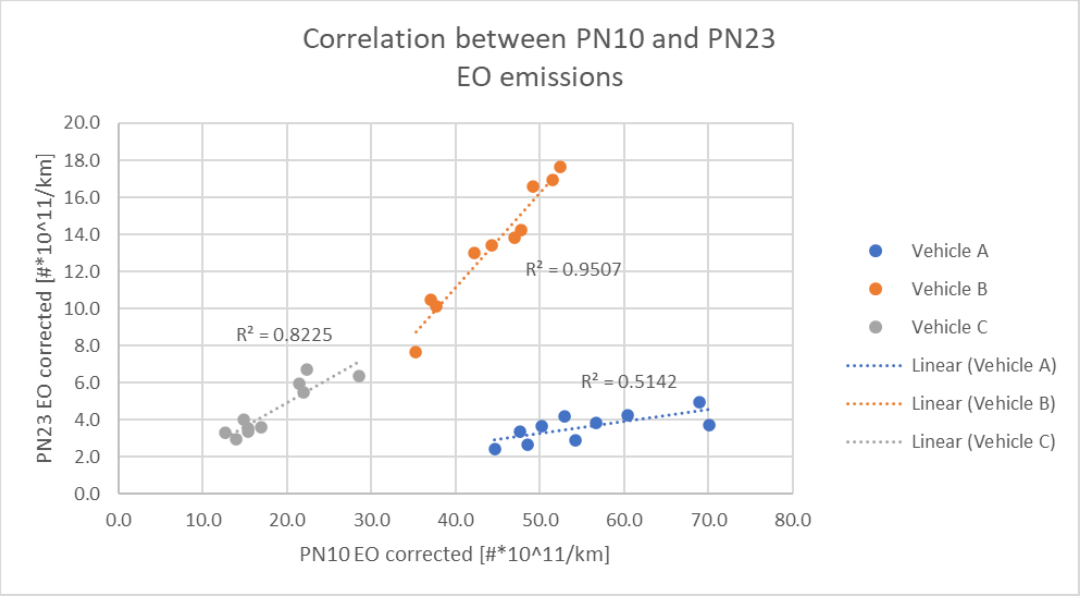


Figure 15.45 Correlation between PN10 EO and PN23 EO emissions

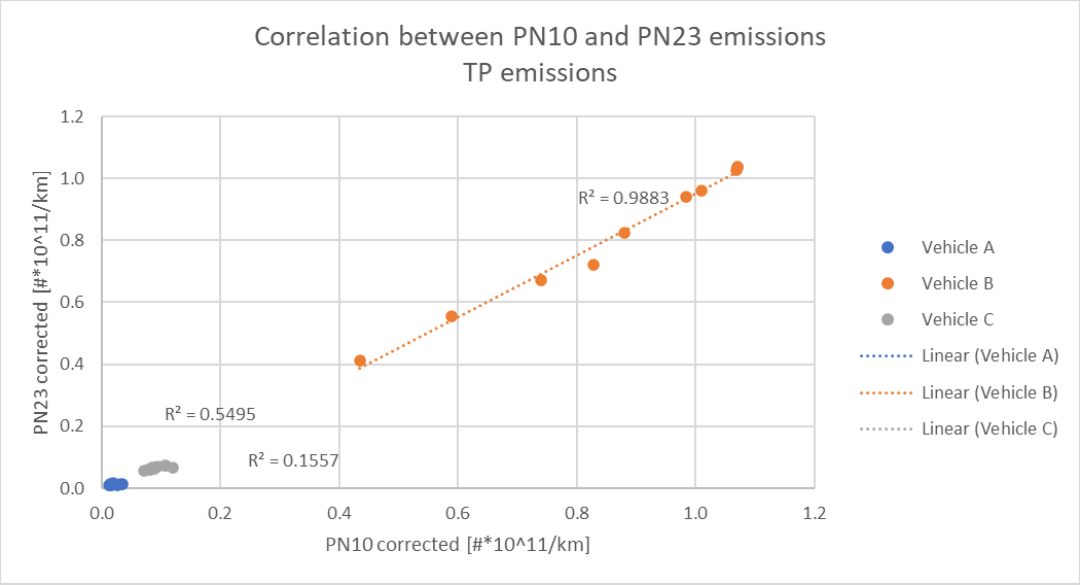


Figure 15.46 Correlation between PN10 TP and PN23 TP emissions

16. PHASE 2 - ANALYSIS OF THE EFFECT OF FUEL CHARACTERISTICS ON PARTICULATE EMISSIONS

16.1. METHODS FOR ANALYSING THE FUEL EFFECT

The corrected fuel trends with neglected fuels effects account for compensating changes in vehicle behaviour i.e., vehicle settling. However, in experimental tests, non-fuel dependent, natural deviation in emission formation occurs. This deviation is considered as pure error between repetitions. Measurement equipment and post processing uncertainties, test driver consistency or simply tolerances in vehicle technology are typically responsible for the differences between test repetitions.

The assessment of the fuel effect is addressed by assuming that the differences caused by the fuel characteristics are represented as the mean value of the corrected residuals for each fuel and the difference between the residuals between repetitions are representing the deviation caused by pure error. In this case, the standard deviation for each fuel was calculated individually, representing the uncertainty caused by the error contributing factors.

16.2. CORRELATION OF FUEL CHARACTERISTICS AND PN EMISSIONS

The fuel effect and its correlation with PN and PM results were screened by mapping of initial fuel correlation. First, the correlation of both uncorrected and corrected measurements was studied in MS excel by comparing the correlation coefficient (r-value) for each PN result and fuel characteristics. For the mapping, the test results were split into phases following: RDE (complete test), Phase 1 (cold start urban part) and “static points” collected from even parts of the test sequence. Five static points were checked in total: Rural 1, rural 2, highway 1, highway 2 and motorway. The correlation coefficient (r) was calculated for each data set (PN result on vehicle basis) in respect to the fuel properties declared by the members of Concawe. The mapping of the correlation for both uncorrected and corrected data are shown in Table 16.1 and ***Table 16.2***. Each number presented in Table 16.1 corresponds to the correlation between the given fuel property and the PN data obtained from each test phase. The map indicates stronger correlations in different contrasts of green color, meanwhile less significant correlation is shown in red. Positive values indicate that an increase in given fuel property increase PN emissions and vice versa.

After the initial mapping of correlations, a threshold limit for the correlation coefficient of 0.6 (abs) was set. All fuel properties that had a lower correlation coefficient than 0.6 were discarded. The threshold number was manually iterated so that the most significant (or any correlation) between fuel properties and the PN emissions for all vehicles could be determined. The main purpose of the filtering was to reduce the number of variables for any further PN modelling and to avoid discarding any central variables based on pure mathematics. The result of the filtering is shown in Table 16.3. Due to the filtering, a preliminary conclusion of most significant fuel properties for PN emissions could be concluded. Based on the findings presented in Table 16.3, the influence of fuel parameters was generally strongest for vehicle B and the effect of any correlations apply similarly for both its PN EO and PN TP emissions. However, conjunctive variables were found for all vehicles. Primarily, aromatics and/or fuel distillation curve seem to influence mostly all vehicles.

As a summary, following variables that exceeded the r > 0.6, or r < -0.6 threshold were found:

Vehicle A (corrected)
PN10 EO: IBP + 50 vol%
PN23 EO: IBP + E70 + E100 + DVPE + Aromatics
PN10 TP: IBP + 50 %vol + 80 %vol + E100 + E150
PN23 TP: No fuel properties with a sufficient r value were found

Vehicle B (uncorrected)
PN10 EO: 10 %vol + Aromatics + C9 and >C9 aromatics
PN23 EO: 10 %vol + Aromatics + C9 and >C9 aromatics + <C9 aromatics
PN10 TP: Aromatics + E70 + DVPE + ETBE
PN23 TP: Aromatics + E70 + DVPE + ETBE

Vehicle B (corrected)
PN10 EO: 10 %vol + DVPE + Aromatics + C9 and >C9 aromatics + ETBE
PN23 EO: 10 %vol + Aromatics + <C9 aromatics
PN10 TP: Aromatics + E70 + DVPE
PN23 TP: Aromatics + E70 + DVPE + ETBE

Vehicle C (corrected)
PN10 EO: 20 %vol + 95 %vol + C9 and >C9 aromatics
PN23 EO: 10 %vol + 20 vol % + C9 and >C9 aromatics
PN10 TP: 5 %vol* + 30 %vol + Ethanol + ETBE
PN23 TP: 30 %vol + <C9 aromatics

*due to lack of data, 5% vol was discarded as an input. Not all fuels used in the tests were distributed giving 5% vol yield information.

Table 16.1 Mapping of the correlation between fuel average, uncorrected PN data and declared fuel properties

Correlation map, uncorrected		RON	MON	Density	IBP	5	10	20	30	40	50	60	70	80	90	95	FBP	E70	E100	E150	DVPE	Olefins	Aromatics	C9 and C9+ aro	<C9 Aromatics	Oxygen	Ethanol	ETBE	MTBE
						(Vol %)																(%v/v)				(%m/m)		(%v/v)	
PN10 raw	RDE	0.01	0.01	-0.36	0.16	0.58	0.54	0.59	0.40	0.26	0.19	-0.23	-0.40	-0.59	-0.72	-0.74	-0.28	-0.34	0.03	0.67	-0.38	-0.30	-0.25	-0.39	-0.08	0.23	0.03	0.32	0.02
	Phase 1	0.02	-0.01	0.35	-0.52	-0.44	-0.60	-0.59	-0.48	-0.67	-0.71	-0.74	-0.62	-0.18	-0.07	0.06	-0.17	0.58	0.84	0.15	0.64	0.07	0.46	0.54	0.27	0.57	0.55	-0.34	-0.03
	Rural 1	0.18	0.16	0.22	-0.08	-0.12	-0.16	-0.39	-0.32	-0.26	-0.08	-0.02	0.03	-0.03	0.10	0.23	0.09	0.21	0.15	-0.07	0.03	0.49	0.34	0.36	0.22	0.06	0.07	0.08	-0.21
	Rural 2	0.23	0.22	0.09	-0.34	-0.10	-0.17	-0.33	-0.19	-0.38	-0.41	-0.20	-0.08	-0.31	-0.11	0.11	0.08	0.22	0.35	0.16	0.21	0.08	0.36	0.52	0.15	-0.01	-0.04	0.19	-0.25
	HW1	0.14	0.13	-0.17	-0.02	0.50	0.30	0.14	0.16	0.06	0.07	-0.05	-0.13	-0.53	-0.38	-0.20	0.07	-0.19	0.06	0.41	-0.26	0.10	-0.02	0.11	-0.10	-0.06	-0.19	0.47	-0.12
	MW1	0.02	0.01	0.02	-0.22	0.18	-0.19	-0.30	-0.30	-0.29	-0.17	-0.07	-0.01	-0.27	-0.16	-0.03	-0.03	0.22	0.20	0.23	0.12	0.40	0.35	0.36	0.24	-0.03	0.00	0.07	-0.02
	MW2	0.19	0.17	0.00	-0.14	0.33	0.04	-0.05	-0.11	-0.19	-0.15	-0.25	-0.26	-0.54	-0.46	-0.35	-0.23	0.09	0.29	0.51	-0.01	0.18	0.19	0.13	0.18	0.14	0.05	0.28	-0.17
PN23 raw	RDE	-0.08	-0.11	0.17	-0.73	-0.38	-0.78	-0.60	-0.66	-0.86	-0.86	-0.64	-0.40	-0.22	-0.29	-0.25	-0.44	0.76	0.79	0.36	0.86	0.01	0.77	0.60	0.65	0.45	0.56	-0.56	0.10
	Phase 1	0.06	0.03	0.20	-0.40	-0.51	-0.56	-0.61	-0.52	-0.68	-0.72	-0.75	-0.64	-0.08	-0.05	0.01	-0.21	0.64	0.80	0.12	0.60	0.16	0.28	0.37	0.14	0.71	0.72	-0.49	-0.06
	Rural 1	0.17	0.15	0.44	-0.47	-0.53	-0.65	-0.69	-0.53	-0.55	-0.47	-0.12	0.05	0.22	0.37	0.50	0.11	0.51	0.36	-0.33	0.57	0.23	0.55	0.67	0.32	0.10	0.19	-0.24	-0.19
	Rural 2	0.16	0.16	0.17	-0.48	-0.23	-0.42	-0.47	-0.33	-0.42	-0.36	0.12	0.29	0.05	0.21	0.40	0.23	0.30	0.13	-0.18	0.41	0.09	0.52	0.69	0.26	-0.20	-0.11	-0.01	-0.17
	HW1	-0.11	-0.12	0.01	-0.77	-0.05	-0.46	-0.35	-0.20	-0.48	-0.54	-0.20	-0.08	-0.21	-0.06	0.20	0.24	0.28	0.42	0.10	0.58	-0.27	0.58	0.86	0.22	-0.03	-0.01	-0.10	0.13
	MW1	-0.07	-0.09	0.03	-0.76	-0.28	-0.70	-0.67	-0.53	-0.74	-0.74	-0.30	-0.08	-0.10	0.01	0.21	0.08	0.60	0.55	0.07	0.76	0.06	0.64	0.86	0.32	0.11	0.23	-0.38	0.09
	MW2	-0.04	-0.07	0.18	-0.78	-0.39	-0.82	-0.74	-0.66	-0.82	-0.77	-0.37	-0.14	-0.04	0.01	0.15	-0.08	0.71	0.62	0.06	0.84	0.12	0.75	0.83	0.49	0.24	0.38	-0.48	0.06
PN10 tailpipe	RDE	0.16	0.19	-0.27	0.75	0.11	0.82	0.62	0.62	0.70	0.66	0.46	0.32	0.18	0.11	0.03	0.23	-0.65	-0.67	-0.21	-0.82	-0.15	-0.65	-0.66	-0.46	-0.28	-0.40	0.43	-0.20
	Phase 1	-0.36	-0.37	-0.01	-0.26	-0.19	-0.31	-0.47	-0.19	-0.28	-0.30	-0.19	-0.09	0.05	0.30	0.52	0.46	0.21	0.30	-0.20	0.23	0.27	0.22	0.61	-0.10	-0.09	-0.02	-0.20	0.33
	Rural 1	0.14	0.14	0.41	0.21	-0.46	-0.12	-0.27	-0.26	0.02	0.28	0.37	0.41	0.57	0.54	0.50	0.17	0.06	-0.28	-0.61	-0.12	0.43	0.26	0.11	0.29	-0.08	0.00	-0.08	-0.19
	Rural 2	0.21	0.22	0.39	0.43	-0.62	-0.07	-0.33	-0.26	0.08	0.32	0.45	0.50	0.76	0.75	0.65	0.21	0.07	-0.39	-0.80	-0.20	0.56	0.02	-0.09	0.09	-0.11	0.00	-0.13	-0.28
	HW1	0.26	0.26	0.49	0.30	-0.60	-0.13	-0.42	-0.27	-0.02	0.16	0.23	0.27	0.57	0.68	0.68	0.25	0.12	-0.14	-0.70	-0.12	0.54	0.06	0.08	0.04	-0.01	0.04	-0.03	-0.33
	MW1	0.14	0.14	0.56	-0.29	0.27	0.05	0.23	0.28	0.17	0.06	-0.13	-0.22	-0.42	-0.16	0.03	0.04	-0.29	0.21	0.14	0.00	-0.42	0.30	0.30	0.22	-0.17	-0.39	0.64	-0.14
	MW2	0.23	0.23	0.61	-0.15	-0.01	-0.04	0.00	0.13	0.10	0.03	-0.06	-0.10	-0.15	0.13	0.28	0.11	-0.16	0.16	-0.13	0.01	-0.18	0.20	0.25	0.11	-0.15	-0.29	0.50	-0.25
PN23 tail pipe	RDE	-0.07	-0.07	-0.16	0.51	0.07	0.50	0.48	0.33	0.33	0.26	-0.03	-0.02	-0.16	-0.31	-0.45	-0.31	-0.30	-0.19	0.27	-0.49	-0.12	-0.24	-0.60	0.06	-0.12	-0.18	0.19	0.05
	Phase 1	-0.24	-0.25	-0.11	-0.17	-0.48	-0.43	-0.68	-0.42	-0.45	-0.42	-0.20	-0.05	0.30	0.44	0.57	0.39	0.45	0.30	-0.33	0.33	0.47	0.09	0.48	-0.20	0.13	0.29	-0.51	0.20
	Rural 1	0.09	0.07	-0.12	-0.20	-0.30	-0.31	-0.61	-0.39	-0.52	-0.53	-0.37	-0.26	-0.06	0.11	0.28	0.18	0.46	0.45	0.00	0.30	0.42	0.03	0.40	-0.22	0.30	0.36	-0.26	-0.11
	Rural 2	0.21	0.20	0.13	-0.06	-0.55	-0.35	-0.67	-0.52	-0.47	-0.31	-0.04	0.12	0.29	0.38	0.47	0.17	0.46	0.18	-0.33	0.21	0.58	0.25	0.39	0.09	0.17	0.28	-0.27	-0.26
	HW1	0.21	0.19	0.20	0.01	-0.59	-0.34	-0.67	-0.44	-0.40	-0.33	-0.18	-0.07	0.29	0.46	0.54	0.20	0.43	0.28	-0.38	0.20	0.56	0.03	0.28	-0.14	0.25	0.33	-0.26	-0.26
	MW1	0.25	0.24	0.22	0.12	-0.57	-0.23	-0.57	-0.31	-0.27	-0.26	-0.14	-0.05	0.30	0.50	0.56	0.21	0.32	0.20	-0.42	0.11	0.48	-0.14	0.13	-0.28	0.17	0.23	-0.15	-0.30
	MW2	0.14	0.12	-0.02	-0.32	-0.37	-0.42	-0.68	-0.46	-0.62	-0.62	-0.40	-0.26	-0.07	0.10	0.27	0.11	0.54	0.53	0.01	0.42	0.37	0.17	0.50	-0.09	0.33	0.39	-0.27	-0.16
PM tail pipe	RDE	0.15	0.17	-0.58	0.40	0.26	0.74	0.53	0.66	0.45	0.22	0.17	0.08	-0.20	-0.14	-0.07	0.31	-0.53	-0.35	0.12	-0.56	-0.38	-0.72	-0.40	-0.72	-0.23	-0.37	0.44	-0.16
PN10 raw	RDE	-0.45	-0.47	0.30	-0.48	-0.36	-0.65	-0.45	-0.44	-0.39	-0.26	-0.15	-0.05	0.32	0.28	0.30	0.08	0.40	0.31	-0.27	0.56	0.08	0.65	0.60	0.50	0.12	0.27	-0.58	0.45
	Phase 1	-0.08	-0.11	0.38	-0.37	-0.41	-0.52	-0.32	-0.43	-0.51	-0.51	-0.74	-0.69	-0.09	-0.21	-0.27	-0.47	0.51	0.74	0.22	0.55	-0.06	0.44	0.19	0.47	0.73	0.71	-0.49	0.09
	Rural 1	-0.22	-0.23	0.32	-0.22	-0.47	-0.64	-0.53	-0.63	-0.38	-0.11	0.26	0.46	0.56	0.41	0.31	-0.09	0.47	-0.06	-0.42	0.43	0.42	0.68	0.37	0.69	-0.14	0.13	-0.56	0.20
	Rural 2	-0.44	-0.44	0.51	-0.45	-0.20	-0.53	-0.25	-0.24	-0.12	0.02	0.15	0.23	0.34	0.38	0.43	0.20	0.12	0.05	-0.40	0.40	-0.06	0.74	0.63	0.60	-0.28	-0.16	-0.23	0.43
	HW1	-0.09	-0.09	0.42	-0.69	-0.06	-0.67	-0.38	-0.37	-0.33	-0.24	0.11	0.18	0.14	0.21	0.29	0.07	0.30	0.17	-0.21	0.64	-0.09	0.67	0.69	0.47	-0.12	-0.02	-0.18	0.12
	MW1	0.02	0.00	0.12	-0.65	-0.44	-0.94	-0.88	-0.91	-0.88	-0.70	-0.17	0.07	0.22	0.14	0.13	-0.22	0.88	0.44	-0.07	0.88	0.44	0.67	0.63	0.51	0.30	0.56	-0.73	0.00
	MW2	0.07	0.04	0.45	-0.28	-0.77	-0.85	-0.87	-0.87	-0.75	-0.62	-0.37	-0.13	0.35	0.30	0.22	-0.35	0.85	0.52	-0.22	0.70	0.55	0.50	0.31	0.48	0.41	0.63	-0.69	-0.08
PN23 raw	RDE	-0.46	-0.47	0.32	-0.50	-0.40	-0.74	-0.56	-0.57	-0.48	-0.30	-0.02	0.18	0.35	0.31	0.33	0.04	0.48	0.24	-0.29	0.60	0.23	0.84	0.69	0.69	-0.08	0.14	-0.58	0.45
	Phase 1	-0.16	-0.19	0.34	-0.50	-0.58	-0.76	-0.57	-0.67	-0.71	-0.63	-0.51	-0.29	0.09	-0.05	-0.11	-0.43	0.71	0.62	0.08	0.74	0.10	0.74	0.44	0.73	0.43	0.57	-0.66	0.16
	Rural 1	-0.26	-0.28	0.32	-0.38	-0.47	-0.75	-0.62	-0.72	-0.55	-0.30	0.01	0.23	0.38	0.25	0.19	-0.18	0.60	0.19	-0.24	0.57	0.42	0.81	0.51	0.78	0.03	0.28	-0.63	0.26
	Rural 2	-0.46	-0.48	0.52	-0.51	-0.26	-0.64	-0.36	-0.38	-0.28	-0.15	-0.02	0.11	0.25	0.27	0.33	0.07	0.27	0.23	-0.28	0.50	0.03	0.86	0.68	0.73	-0.17	-0.04	-0.33	0.45
	HW1	-0.15	-0.16	0.35	-0.79	-0.19	-0.85	-0.59	-0.64	-0.62	-0.48	-0.08	0.09	0.08	0.08	0.14	-0.12	0.58	0.37	-0.05	0.81	0.09	0.89	0.78	0.70	0.03	0.20	-0.43	0.18
	MW1	-0.03	-0.05	0.20	-0.61	-0.55	-0.95	-0.88	-0.92	-0.91	-0.76	-0.33	-0.07	0.18	0.09	0.07	-0.32	0.92	0.56	-0.01	0.89	0.42	0.73	0.60	0.60	0.37	0.62	-0.77	0.04
	MW2	0.00	-0.04	0.34	-0.39	-0.68	-0.85	-0.84	-0.86	-0.83	-0.72	-0.47	-0.21	0.18	0.12	0.07	-0.40	0.87	0.63	-0.03	0.74	0.48	0.60	0.40	0.55	0.43	0.63	-0.70	0.00
PN10 tailpipe	RDE	-0.05	-0.08	0.29	-0.65	-0.54	-0.94	-0.85	-0.88	-0.89	-0.74	-0.41	-0.17	0.12	0.07	0.08	-0.29	0.87	0.63	0.00	0.88	0.36	0.78	0.66	0.64	0.41	0.61	-0.704	0.06
	Phase 1	0.00	-0.01	-0.15	-0.21	0.23	0.21	0.44	0.30	-0.05	-0.30	-0.61	-0.63	-0.67	-0.78	-0.77	-0.46	-0.09	0.45	0.75	0.08	-0.70	0.02	-0.15	0.13	0.34	0.14	0.15	0.04
	Rural 1	-0.03	-0.06	0.36	-0.57	-0.55	-0.93	-0.86	-0.90	-0.83	-0.63	-0.27	-0.03	0.22	0.17	0.16	-0.27	0.84	0.52	-0.10	0.81	0.47	0.80	0.63	0.68	0.31	0.53	-0.66	0.03
	Rural 2	-0.05	-0.08	0.48	-0.40	-0.29	-0.68	-0.55	-0.70	-0.61	-0.43	-0.51	-0.42	-0.05	-0.14	-0.19	-0.49	0.64	0.62	0.17	0.57	0.38	0.67	0.33	0.70	0.55	0.62	-0.47	0.06
	HW1	0.01	-0.02	0.29	-0.60	-0.50	-0.94	-0.86	-0.92	-0.86	-0.67	-0.25	0.00	0.18	0.11	0.08	-0.33	0.88	0.50	-0.04	0.84	0.46	0.78	0.60	0.68	0.31	0.54	-0.68	0.01
	MW1	0.04	0.01	0.15	-0.68	-0.49	-0.95	-0.90	-0.91	-0.96	-0.84	-0.41	-0.16	0.07	0.02	0.04	-0.30	0.94	0.64	0.07	0.93	0.39	0.67	0.64	0.50	0.43	0.65	-0.72	-0.01
	MW2	-0.14	-0.17	0.19	-0.41	-0.62	-0.84	-0.86	-0.82	-0.81	-0.72	-0.45	-0.19	0.19	0.16	0.14	-0.26	0.85	0.60	-0.05	0.74	0.50	0.52	0.45	0.42	0.36	0.59	-0.75	0.13
PN23 tail pipe	RDE	-0.04	-0.07	0.25	-0.62	-0.58	-0.93	-0.86	-0.88	-0.90	-0.75	-0.40	-0.16	0.16	0.09	0.09	-0.28	0.89	0.62	-0.02	0.87	0.37	0.74	0.63	0.60	0.43	0.64	-0.75	0.05
	Phase 1	0.29	0.28	-0.09	-0.07	0.09	0.23	0.38	0.24	-0.08	-0.31	-0.62	-0.67	-0.59	-0.72	-0.78	-0.56	-0.02	0.44	0.69	0.05	-0.61	-0.15	-0.34	0.02	0.54	0.32	0.15	-0.26
	Rural 1	-0.04	-0.07	0.31	-0.53	-0.60	-0.93	-0.89	-0.92	-0.85	-0.65	-0.27	-0.01	0.27	0.20	0.17	-0.27	0.88	0.50	-0.13	0.81	0.51	0.75	0.58	0.65	0.33	0.57	-0.74	0.05
	Rural 2	-0.11	-0.15	0.57	-0.49	-0.53	-0.80	-0.63	-0.72	-0.67	-0.55	-0.58	-0.45	0.08	0.02	-0.02	-0.42	0.70	0.71	0.02	0.72	0.25	0.73	0.45	0.70	0.56	0.65	-0.59	0.11
	HW1	-0.01	-0.03	0.27	-0.59	-0.53	-0.95	-0.87	-0.93	-0.87	-0.69	-0.26	0.01	0.21	0.12	0.09	-0.33	0.89	0.50	-0.05	0.85	0.45	0.76	0.59	0.66	0.31	0.56	-0.72	0.02
	MW1	0.04	0.01	0.15	-0.67	-0.50	-0.95	-0.90	-0.91	-0.96	-0.84	-0.41	-0.15	0.08	0.03	0.04	-0.30	0.94	0.64	0.07	0.92	0.40	0.67	0.63	0.51	0.43	0.65	-0.72	-0.01
	MW2	-0.13	-0.17	0.19	-0.41	-0.60	-0.84	-0.85	-0.82	-0.82	-0.73	-0.47	-0.20	0.16	0.14	0.12	-0.28	0.85	0.61	-0.02	0.74	0.49	0.52	0.45	0.42	0.37	0.59	-0.74	0.13
PM tail pipe	RDE	0.14	0.13	0.30	0.18	0.21	0.44	0.51	0.38	0.25	0.13	-0.40	-0.47	-0.60	-0.58	-0.55	-0.41	-0.34	0.24	0.53	-0.36	-0.36	0.08	-0.28	0.30	0.11	-0.15	0.58	-0.16
PN10 raw	RDE	-0.25	-0.26	-0.23	-0.38	-0.37	-0.57	-0.72	-0.50	-0.49	-0.37	0.22	0.41	0.47	0.55	0.67	0.51	0.47	0.01	-0.47	0.47	0.43	0.29	0.69	-0.05	-0.17	0.09	-0.58	0.24
	Phase 1	-0.15	-0.15	-0.12	-0.48	-0.31	-0.66	-0.77	-0.58	-0.54	-0.38	0.19	0.35	0.43	0.50	0.61	0.42	0.53	0.07	-0.43	0.57	0.44	0.36	0.72	0.01	-0.06	0.19	-0.56	0.15
	Rural 1	-0.79	-0.80	-0.08	-0.10	-0.29	-0.43	-0.30	-0.26	-0.14	-0.09	0.02	0.16	0.47	0.39	0.32	0.18	0.25	0.01	-0.34	0.30	0.21	0.24	0.24	0.18	-0.20	0.06	-0.71	0.78
	Rural 2	-0.13	-0.14	-0.47	-0.05	-0.22	-0.19	-0.55	-0.30	-0.37	-0.35	0.05	0.22	0.16	0.29	0.43	0.42	0.34	0.04	-0.17	0.14	0.52	-0.08	0.36	-0.34	-0.13	0.06	-0.33	0.10
	HW1	-0.04	-0.04	-0.38	-0.40	-0.23	-0.45	-0.68	-0.42	-0.53	-0.49	0.08	0.24	0.22	0.35	0.52	0.47	0.46	0.12	-0.25	0.46	0.35	0.09	0.63	-0.29	-0.03	0.16	-0.43	0.04
	MW1	-0.60	-0.60	-0.25	-0.14	-0.19	-0.21	-0.37	-0.09	-0.09	-0.03	0.20	0.28	0.40	0.55	0.72	0.74	0.06	-0.09	-0.49	0.10	0.27	0.13	0.58	-0.20	-0.33	-0.17	-0.36	0.56
	MW2	-0.83	-0.83	-0.30	-0.01	0.02	-0.01	-0.02	0.22	0.23	0.19	0.21	0.20	0.36	0.48	0.60	0.74	-0.21	-0.20	-0.44	-0.06	0.00	-0.08	0.33	-0.33	-0.45	-0.33	-0.29	0.81
PN23 raw	RDE	-0.14	-0.14	-0.08	-0.51	-0.24	-0.57	-0.60	-0.44	-0.45	-0.33	0.14	0.23	0.35	0.41	0.54	0.41	0.41	0.10	-0.38	0.54	0.22	0.34	0.70	0.01	0.00	0.18	-0.47	0.15
	Phase 1	-0.06	-0.06	0.13	-0.61	-0.07	-0.59	-0.41	-0.40	-0.39	-0.27	0.04	0.06	0.18	0.18	0.23	0.12	0.36	0.18	-0.18	0.60	0.00	0.44	0.58	0.22	0.15	0.25	-0.37	0.10
	Rural 1	-0.52	-0.51	-0.30	-0.14	-0.23	-0.41	-0.47	-0.26	-0.12	-0.03	0.45	0.56	0.68	0.72	0.75	0.63	0.21	-0.30	-0.66	0.27	0.34	0.00	0.41	-0.26	-0.40	-0.10	-0.60	0.51
	Rural 2	-0.02	-0.02	-0.34	-0.03	-0.37	-0.21	-0.60	-0.30	-0.36	-0.36	0.02	0.17	0.26	0.42	0.56	0.47	0.34	0.07	-0.31	0.15	0.49	-0.15	0.35	-0.43	-0.03	0.12	-0.32	-0.02
	HW1	0.12	0.12	-0.23	-0.61	0.01	-0.55	-0.47	-0.42	-0.51	-0.47	0.02	0.08	0.06	0.06	0.11	0.09	0.47	0.18	-0.01	0.65	0.03	0.15	0.46	-0.10	0.18	0.32	-0.40	-0.06
	MW1	-0.73	-0.73	-0.35	-0.18	-0.05	-0.19	-0.31	-0.06	-0.08	-0.04	0.18	0.27	0.29	0.42	0.61	0.72	0.04	-0.08	-0.35	0.09	0.24	0.17	0.61	-0.16	-0.40	-0.22	-0.36	0.70
	MW2	-0.18	-0.18	-0.36	-0.10	-0.28	-0.21	-0.56	-0.24	-0.31	-0.30	0.04	0.16	0.26	0.43	0.61	0.58	0.27	0.06	-0.33	0.15	0.44	-0.08	0.46	-0.42	-0.09	0.06	-0.33	0.14
PN10 tailpipe	RDE	-0.38	-0.39	-0.15	-0.19	0.53	0.32	0.40	0.58	0.30	0.06	-0.16	-0.24	-0.54	-0.26	0.01	0.39	-0.47	0.13	0.30	-0.19	-0.50	-0.05	0.28	-0.25	-0.38	-0.55	0.50	0.39
	Phase 1	-0.22	-0.22	-0.63	0.17	0.27	0.38	0.20	0.37	0.13	-0.10	-0.19	-0.21	-0.33	-0.21	-0.10	0.25	-0.20	0.05	0.30	-0.25	-0.12	-0.54	-0.15	-0.65	-0.09	-0.14	0.09	0.22
	Rural 1	-0.29	-0.28	-0.03	-0.11	0.75	0.58	0.79	0.84	0.61	0.40	0.04	-0.16	-0.58	-0.38	-0.15	0.34	-0.80	-0.11	0.33	-0.41	-0.79	-0.04	0.12	-0.13	-0.46	-0.74	0.79	0.31
	Rural 2	-0.30	-0.30	0.42	-0.37	0.46	0.04	0.32	0.36	0.26	0.18	-0.06	-0.16	-0.40	-0.17	0.05	0.19	-0.39	0.14	0.15	-0.01	-0.46	0.42	0.44	0.29	-0.36	-0.53	0.52	0.31
	HW1	-0.61	-0.61	0.04	-0.31	0.70	0.19	0.47	0.53	0.44	0.34	0.12	-0.03	-0.35	-0.15	0.07	0.44	-0.56	-0.07	0.14	-0.14	-0.50	0.23	0.41	0.04	-0.54	-0.66	0.44	0.63
	MW1	-0.74	-0.74	-0.04	-0.33	0.48	0.13	0.36	0.48	0.29	0.16	-0.03	-0.08	-0.33	-0.13	0.12	0.46	-0.45	0.06	0.14	-0.07	-0.51	0.32	0.52	0.10	-0.52	-0.61	0.28	0.74
	MW2	-0.51	-0.52	0.38	-0.37	0.37	0.01	0.33	0.36	0.22	0.10	-0.27	-0.36	-0.41	-0.22	-0.02	0.15	-0.35	0.29	0.21	0.04	-0.53	0.44	0.43	0.32	-0.23	-0.40	0.35	0.51
PN23 tail pipe	RDE	-0.53	-0.53	-0.62	0.13	0.22	0.26	0.13	0.35	0.18	-0.01	-0.07	-0.08	-0.09	0.03	0.15	0.47	-0.21	-0.04	0.06	-0.19	-0.06	-0.46	0.00	-0.63	-0.24	-0.21	-0.09	0.52
	Phase 1	-0.28	-0.27	-0.59	0.32	0.09	0.31	0.11	0.28	0.16	-0.04	-0.12	-0.13	-0.06	0.01	0.03	0.25	-0.14	-0.05	0.08	-0.25	0.04	-0.64	-0.28	-0.69	-0.07	-0.05	-0.10	0.27
	Rural 1	-0.60	-0.60	0.07	-0.02	0.47	0.01	0.23	0.13	0.34	0.46	0.24	0.11	0.05	0.05	0.04	0.17	-0.28	-0.23	-0.06	-0.14	0.07	0.17	0.09	0.18	-0.33	-0.29	0.01	0.61
	Rural 2	-0.55	-0.55	0.28	-0.24	0.30	-0.26	-0.01	-0.08	0.14	0.31	0.23	0.16	0.15	0.18	0.21	0.19	-0.09	-0.11	-0.19	0.11	0.11	0.44	0.35	0.37	-0.30	-0.22	-0.09	0.57
	HW1	-0.27	-0.27	0.22	-0.28	0.43	-0.20	-0.03	-0.05	0.09	0.21	0.17	0.06	-0.05	0.07	0.14	0.17	-0.08	-0.03	-0.05	0.11	0.11	0.28	0.34	0.16	-0.21	-0.19	0.09	0.30
	MW1	-0.65	-0.65	-0.10	-0.40	0.44	0.09	0.24	0.42	0.18	0.02	-0.10	-0.14	-0.38	-0.12	0.18	0.52	-0.36	0.15	0.16	0.00	-0.46	0.27	0.60	-0.02	-0.45	-0.54	0.27	0.65
	MW2	-0.30	-0.32	0.56	-0.37	0.22	-0.08	0.23	0.23	0.10	-0.02	-0.46	-0.56	-0.44	-0.26	-0.10	-0.04	-0.20	0.48	0.25	0.13	-0.47	0.45	0.36	0.38	0.05	-0.15	0.32	0.31
PM tail pipe	RDE	-0.10	-0.09	-0.47	0.01	0.33	0.53	0.40	0.55	0.26	0.11	0.08	0.03	-0.34	-0.22	0.01	0.45	-0.46	-0.14	0.19	-0.36	-0.42	-0.18	0.16	-0.35	-0.29	-0.44	0.42	0.09

Table 16.2 Mapping of the correlation between fuel average, corrected PN data and declared fuel properties

Correlation map, corrected		RON	MON	Density	IBP	5	10	20	30	40	50	60	70	80	90	95	FBP	E70	E100	E150	DVPE	Olefins	Aromatics	C9 and C9+ aro	<C9 Aromatics	Oxygen	Ethanol	ETBE	MTBE
						(Vol %)																(%v/v)				(%m/m)	(%v/v)		
PN10 raw	RDE	0.22	0.20	0.23	-0.66	0.01	-0.44	-0.31	-0.32	-0.56	-0.63	-0.41	-0.26	-0.52	-0.40	-0.24	-0.31	0.40	0.59	0.46	0.56	-0.15	0.59	0.54	0.46	0.13	0.10	0.09	-0.19
	Phase 1	0.14	0.11	0.18	-0.48	-0.26	-0.37	-0.43	-0.28	-0.56	-0.68	-0.71	-0.62	-0.38	-0.20	0.00	-0.07	0.42	0.78	0.28	0.47	-0.04	0.30	0.51	0.08	0.49	0.40	-0.09	-0.14
	Rural 1	0.22	0.21	0.19	-0.16	-0.15	-0.14	-0.38	-0.23	-0.27	-0.19	-0.06	0.00	-0.09	0.11	0.31	0.20	0.17	0.21	-0.07	0.07	0.33	0.29	0.45	0.10	0.02	0.00	0.16	-0.25
	Rural 2	0.23	0.22	-0.04	-0.28	0.01	0.05	-0.11	0.06	-0.23	-0.34	-0.21	-0.13	-0.41	-0.20	0.05	0.16	0.02	0.29	0.23	0.07	-0.15	0.20	0.43	-0.01	-0.04	-0.15	0.34	-0.24
	HW1	0.16	0.16	-0.09	-0.17	0.40	0.24	0.09	0.21	0.01	-0.07	-0.11	-0.16	-0.55	-0.31	-0.04	0.21	-0.19	0.17	0.34	-0.15	-0.07	0.04	0.30	-0.14	-0.11	-0.27	0.54	-0.16
	MW1	0.10	0.08	0.10	-0.37	0.02	-0.27	-0.39	-0.27	-0.38	-0.36	-0.15	-0.03	-0.28	-0.07	0.15	0.10	0.26	0.32	0.14	0.26	0.23	0.39	0.55	0.17	-0.06	-0.05	0.11	-0.10
	MW2	0.25	0.23	0.12	-0.36	0.16	-0.08	-0.15	-0.07	-0.29	-0.37	-0.32	-0.27	-0.56	-0.35	-0.13	-0.07	0.12	0.43	0.41	0.17	-0.04	0.30	0.40	0.14	0.06	-0.06	0.35	-0.24
PN23 raw	RDE	-0.03	-0.06	0.18	-0.74	-0.40	-0.79	-0.65	-0.68	-0.88	-0.87	-0.58	-0.33	-0.20	-0.23	-0.16	-0.38	0.77	0.76	0.30	0.86	0.05	0.76	0.65	0.61	0.39	0.50	-0.52	0.05
	Phase 1	0.15	0.12	0.08	-0.37	-0.41	-0.40	-0.51	-0.39	-0.63	-0.72	-0.76	-0.67	-0.23	-0.16	-0.04	-0.16	0.54	0.79	0.23	0.50	0.07	0.17	0.35	0.00	0.68	0.64	-0.33	-0.15
	Rural 1	0.05	0.04	0.49	-0.41	-0.58	-0.55	-0.51	-0.36	-0.40	-0.38	-0.18	-0.06	0.28	0.38	0.48	0.13	0.37	0.35	-0.38	0.51	-0.01	0.48	0.57	0.29	0.15	0.20	-0.26	-0.07
	Rural 2	0.06	0.06	0.22	-0.48	-0.29	-0.39	-0.36	-0.21	-0.32	-0.31	0.09	0.24	0.11	0.26	0.43	0.27	0.20	0.13	-0.26	0.40	-0.11	0.50	0.67	0.25	-0.20	-0.14	-0.03	-0.08
	HW1	-0.21	-0.22	0.07	-0.70	-0.10	-0.41	-0.23	-0.10	-0.37	-0.46	-0.24	-0.16	-0.14	-0.03	0.17	0.21	0.20	0.41	0.04	0.54	-0.40	0.53	0.75	0.23	0.02	0.02	-0.15	0.22
	MW1	-0.17	-0.19	0.02	-0.74	-0.26	-0.59	-0.48	-0.36	-0.64	-0.70	-0.43	-0.26	-0.16	-0.08	0.11	0.07	0.48	0.60	0.13	0.70	-0.18	0.58	0.78	0.28	0.21	0.26	-0.37	0.18
	MW2	-0.08	-0.11	0.18	-0.76	-0.39	-0.74	-0.62	-0.54	-0.75	-0.75	-0.44	-0.24	-0.07	-0.02	0.13	-0.05	0.62	0.65	0.07	0.80	-0.05	0.69	0.79	0.43	0.27	0.37	-0.45	0.09
PN10 tailpipe	RDE	0.05	0.08	0.11	0.74	-0.33	0.41	0.26	0.25	0.54	0.65	0.59	0.55	0.66	0.55	0.37	0.20	-0.38	-0.70	-0.65	-0.59	0.15	-0.36	-0.54	-0.14	-0.32	-0.28	0.09	-0.12
	Phase 1	-0.21	-0.22	-0.20	-0.20	-0.04	-0.09	-0.33	-0.04	-0.21	-0.28	-0.16	-0.09	-0.11	0.15	0.41	0.50	0.09	0.24	-0.05	0.09	0.18	0.05	0.52	-0.28	-0.12	-0.10	-0.01	0.18
	Rural 1	0.26	0.26	0.21	0.15	-0.39	-0.08	-0.38	-0.28	-0.11	0.11	0.31	0.37	0.40	0.46	0.52	0.28	0.12	-0.19	-0.49	-0.11	0.51	0.17	0.22	0.09	-0.07	-0.01	0.01	-0.31
	Rural 2	0.27	0.28	0.28	0.40	-0.61	-0.04	-0.37	-0.24	0.02	0.23	0.41	0.48	0.68	0.72	0.68	0.29	0.09	-0.35	-0.75	-0.20	0.56	-0.04	-0.02	-0.04	-0.11	-0.01	-0.08	-0.34
	HW1	0.34	0.34	0.28	0.22	-0.48	-0.02	-0.37	-0.15	-0.06	0.03	0.16	0.20	0.35	0.53	0.63	0.34	0.07	-0.08	-0.53	-0.14	0.41	-0.04	0.15	-0.15	-0.03	-0.02	0.11	-0.40
	MW1	0.15	0.15	0.57	-0.26	0.28	0.06	0.23	0.27	0.18	0.08	-0.14	-0.23	-0.42	-0.17	0.02	0.01	-0.29	0.21	0.15	-0.02	-0.39	0.28	0.27	0.21	-0.15	-0.37	0.64	-0.15
	MW2	-0.08	-0.11	0.18	-0.76	-0.39	-0.74	-0.62	-0.54	-0.75	-0.75	-0.44	-0.24	-0.07	-0.02	0.13	-0.05	0.62	0.65	0.07	0.80	-0.05	0.69	0.79	0.43	0.27	0.37	-0.45	0.09
PN23 tail pipe	RDE	-0.25	-0.25	0.19	0.28	-0.35	-0.04	0.05	-0.06	0.07	0.08	0.04	0.18	0.26	0.12	-0.06	-0.28	0.04	-0.11	-0.13	-0.07	0.06	0.15	-0.27	0.38	-0.21	-0.09	-0.20	0.21
	Phase 1	-0.12	0.59	-0.30	0.00	0.33	0.29	0.26	0.22	0.12	0.05	0.21	0.09	-0.18	-0.23	-0.26	-0.05	-0.16	-0.23	0.18	-0.10	-0.33	-0.43	-0.28	-0.40	0.10	0.00	0.30	-0.52
	Rural 1	0.07	0.17	-0.12	-0.58	0.53	-0.17	0.12	0.00	-0.12	-0.15	0.08	0.00	-0.33	-0.38	-0.35	-0.12	0.03	0.05	0.35	0.37	-0.46	0.19	0.27	0.10	0.04	0.00	0.10	-0.08
	Rural 2	-0.14	0.16	-0.12	-0.45	0.14	-0.39	-0.17	-0.31	-0.31	-0.25	0.04	0.03	0.01	-0.15	-0.24	-0.23	0.32	0.07	0.14	0.50	-0.09	0.14	0.14	0.11	0.26	0.34	-0.31	-0.08
	HW1	0.23	0.18	-0.67	-0.35	0.34	-0.02	-0.06	-0.05	-0.23	-0.24	0.20	0.21	-0.17	-0.24	-0.16	0.16	0.11	-0.11	0.24	0.21	-0.14	-0.09	0.24	-0.27	0.00	0.05	-0.09	-0.11
	MW1	0.29	0.20	0.09	-0.71	0.23	-0.48	-0.38	-0.29	-0.43	-0.45	-0.16	-0.17	-0.28	-0.11	0.07	0.06	0.32	0.38	0.17	0.59	-0.05	0.29	0.62	0.01	0.17	0.16	0.00	-0.15
	MW2	0.20	-0.16	-0.33	-0.65	0.06	-0.54	-0.62	-0.43	-0.57	-0.54	-0.08	0.03	-0.07	0.09	0.33	0.37	0.46	0.31	0.02	0.58	0.30	0.29	0.81	-0.12	0.03	0.18	-0.35	0.18
PM tail pipe	RDE	0.04	0.07	-0.49	0.49	-0.06	0.54	0.31	0.50	0.39	0.20	0.26	0.25	0.17	0.21	0.21	0.37	-0.38	-0.42	-0.21	-0.47	-0.19	-0.73	-0.42	-0.73	-0.29	-0.32	0.17	-0.07
PN10 raw	RDE	-0.42	-0.43	0.20	-0.51	-0.43	-0.74	-0.60	-0.58	-0.51	-0.34	0.02	0.23	0.39	0.35	0.38	0.11	0.51	0.20	-0.32	0.61	0.23	0.77	0.71	0.59	-0.08	0.16	-0.62	0.41
	Phase 1	0.05	0.02	0.17	-0.44	-0.47	-0.64	-0.48	-0.66	-0.78	-0.76	-0.69	-0.47	-0.17	-0.38	-0.48	-0.72	0.76	0.73	0.42	0.70	0.07	0.56	0.19	0.65	0.64	0.73	-0.60	-0.03
	Rural 1	-0.28	-0.29	0.22	-0.25	-0.42	-0.64	-0.53	-0.63	-0.41	-0.16	0.24	0.47	0.49	0.35	0.25	-0.11	0.49	-0.04	-0.34	0.45	0.42	0.68	0.38	0.68	-0.19	0.10	-0.59	0.27
	Rural 2	-0.46	-0.47	0.50	-0.46	-0.17	-0.52	-0.22	-0.21	-0.11	-0.01	0.15	0.25	0.27	0.33	0.40	0.18	0.10	0.06	-0.35	0.39	-0.09	0.77	0.64	0.63	-0.37	-0.25	-0.18	0.45
	HW1	-0.02	-0.03	0.43	-0.67	-0.06	-0.65	-0.38	-0.38	-0.33	-0.23	0.14	0.22	0.13	0.22	0.29	0.05	0.30	0.14	-0.21	0.61	-0.06	0.67	0.67	0.48	-0.16	-0.05	-0.14	0.05
	MW1	0.07	0.05	0.15	-0.65	-0.45	-0.94	-0.88	-0.91	-0.89	-0.71	-0.19	0.04	0.21	0.13	0.12	-0.23	0.89	0.45	-0.06	0.89	0.42	0.67	0.63	0.51	0.33	0.58	-0.72	-0.04
	MW2	0.01	-0.02	0.43	-0.29	-0.76	-0.83	-0.85	-0.83	-0.74	-0.62	-0.40	-0.16	0.31	0.28	0.21	-0.33	0.83	0.55	-0.19	0.68	0.53	0.51	0.33	0.48	0.39	0.60	-0.68	-0.03
PN23 raw	RDE	-0.40	-0.42	0.33	-0.48	-0.45	-0.75	-0.59	-0.61	-0.51	-0.32	-0.02	0.20	0.36	0.31	0.32	-0.01	0.52	0.23	-0.29	0.60	0.27	0.84	0.66	0.72	-0.07	0.17	-0.59	0.39
	Phase 1	-0.11	-0.13	0.29	-0.42	-0.61	-0.72	-0.57	-0.69	-0.72	-0.65	-0.50	-0.26	0.08	-0.09	-0.17	-0.50	0.73	0.60	0.12	0.69	0.15	0.69	0.34	0.72	0.43	0.59	-0.67	0.10
	Rural 1	-0.31	-0.33	0.28	-0.36	-0.44	-0.73	-0.61	-0.71	-0.53	-0.28	0.03	0.26	0.38	0.25	0.18	-0.16	0.58	0.17	-0.23	0.54	0.44	0.80	0.50	0.77	-0.01	0.25	-0.63	0.30
	Rural 2	-0.45	-0.47	0.53	-0.50	-0.24	-0.62	-0.35	-0.36	-0.28	-0.15	-0.03	0.11	0.20	0.24	0.30	0.04	0.26	0.23	-0.24	0.49	0.03	0.87	0.67	0.75	-0.21	-0.08	-0.28	0.44
	HW1	-0.11	-0.13	0.37	-0.78	-0.20	-0.86	-0.59	-0.65	-0.63	-0.48	-0.08	0.08	0.09	0.07	0.12	-0.15	0.59	0.38	-0.05	0.82	0.10	0.87	0.76	0.70	0.06	0.23	-0.43	0.14
	MW1	0.00	-0.02	0.24	-0.62	-0.56	-0.96	-0.88	-0.93	-0.90	-0.73	-0.32	-0.07	0.21	0.11	0.08	-0.32	0.91	0.55	-0.05	0.89	0.41	0.72	0.59	0.60	0.41	0.65	-0.77	0.01
	MW2	-0.05	-0.08	0.32	-0.39	-0.66	-0.84	-0.82	-0.83	-0.81	-0.71	-0.48	-0.22	0.16	0.11	0.07	-0.38	0.85	0.63	-0.02	0.73	0.47	0.60	0.41	0.55	0.40	0.61	-0.69	0.04
PN10 tailpipe	RDE	-0.03	-0.06	0.31	-0.65	-0.54	-0.94	-0.85	-0.88	-0.89	-0.74	-0.41	-0.17	0.13	0.07	0.08	-0.30	0.87	0.63	-0.01	0.88	0.36	0.78	0.65	0.64	0.43	0.63	-0.701	0.04
	Phase 1	-0.05	-0.06	-0.11	-0.29	0.20	0.13	0.39	0.27	-0.10	-0.35	-0.65	-0.66	-0.67	-0.76	-0.74	-0.44	-0.05	0.51	0.74	0.15	-0.72	0.10	-0.06	0.18	0.36	0.17	0.11	0.08
	Rural 1	-0.02	-0.05	0.38	-0.57	-0.55	-0.93	-0.86	-0.90	-0.83	-0.63	-0.28	-0.04	0.22	0.17	0.16	-0.27	0.84	0.52	-0.11	0.82	0.46	0.80	0.63	0.68	0.33	0.54	-0.67	0.03
	Rural 2	-0.07	-0.10	0.48	-0.41	-0.30	-0.68	-0.55	-0.69	-0.60	-0.42	-0.51	-0.43	-0.03	-0.12	-0.17	-0.48	0.63	0.63	0.16	0.58	0.37	0.67	0.35	0.69	0.55	0.63	-0.48	0.08
	HW1	0.00	-0.03	0.31	-0.61	-0.51	-0.95	-0.86	-0.92	-0.86	-0.67	-0.26	-0.02	0.19	0.11	0.09	-0.32	0.87	0.51	-0.05	0.86	0.44	0.79	0.61	0.68	0.33	0.56	-0.69	0.01
	MW1	0.04	0.01	0.17	-0.69	-0.49	-0.96	-0.90	-0.91	-0.95	-0.82	-0.39	-0.15	0.10	0.04	0.05	-0.30	0.93	0.62	0.04	0.93	0.38	0.68	0.64	0.51	0.45	0.66	-0.73	-0.01
	MW2	-0.10	-0.13	0.21	-0.41	-0.63	-0.83	-0.85	-0.82	-0.82	-0.74	-0.49	-0.23	0.16	0.14	0.12	-0.28	0.85	0.63	-0.02	0.74	0.49	0.52	0.44	0.42	0.40	0.61	-0.73	0.09
PN23 tail pipe	RDE	-0.02	-0.04	0.26	-0.61	-0.59	-0.93	-0.86	-0.89	-0.90	-0.75	-0.40	-0.16	0.17	0.09	0.09	-0.30	0.89	0.61	-0.03	0.87	0.38	0.73	0.61	0.60	0.45	0.66	-0.74	0.03
	Phase 1	0.25	0.24	-0.06	-0.18	0.08	0.15	0.33	0.19	-0.15	-0.39	-0.68	-0.71	-0.63	-0.74	-0.77	-0.56	0.03	0.52	0.71	0.14	-0.64	-0.06	-0.23	0.07	0.56	0.34	0.13	-0.22
	Rural 1	-0.03	-0.06	0.32	-0.53	-0.61	-0.94	-0.89	-0.93	-0.85	-0.65	-0.27	-0.02	0.28	0.20	0.16	-0.28	0.88	0.50	-0.13	0.81	0.50	0.75	0.58	0.65	0.34	0.59	-0.74	0.04
	Rural 2	-0.11	-0.15	0.57	-0.48	-0.52	-0.80	-0.63	-0.71	-0.67	-0.54	-0.58	-0.44	0.09	0.02	-0.01	-0.41	0.70	0.71	0.01	0.71	0.26	0.72	0.45	0.70	0.55	0.65	-0.58	0.12
	HW1	-0.01	-0.03	0.29	-0.60	-0.54	-0.96	-0.86	-0.93	-0.87	-0.68	-0.27	-0.01	0.22	0.13	0.09	-0.32	0.89	0.51	-0.06	0.86	0.44	0.77	0.59	0.67	0.34	0.58	-0.72	0.02
	MW1	0.04	0.01	0.17	-0.68	-0.50	-0.96	-0.90	-0.92	-0.95	-0.82	-0.38	-0.14	0.11	0.05	0.05	-0.30	0.94	0.62	0.04	0.93	0.39	0.68	0.63	0.51	0.44	0.66	-0.74	-0.02
	MW2	-0.10	-0.13	0.21	-0.42	-0.61	-0.83	-0.84	-0.81	-0.82	-0.75	-0.51	-0.25	0.13	0.11	0.10	-0.30	0.85	0.65	0.00	0.74	0.47	0.52	0.44	0.42	0.40	0.61	-0.72	0.09
PM tail pipe	RDE	-0.05	-0.07	0.38	0.24	0.12	0.42	0.50	0.39	0.33	0.24	-0.35	-0.43	-0.43	-0.40	-0.38	-0.27	-0.39	0.19	0.34	-0.41	-0.31	0.13	-0.23	0.33	0.05	-0.19	0.50	0.02
PN10 raw	RDE	-0.24	-0.24	-0.20	-0.36	-0.35	-0.53	-0.68	-0.46	-0.44	-0.31	0.25	0.42	0.48	0.57	0.70	0.54	0.42	-0.02	-0.50	0.44	0.40	0.28	0.69	-0.07	-0.18	0.07	-0.53	0.23
	Phase 1	-0.33	-0.33	-0.12	-0.44	-0.22	-0.60	-0.67	-0.51	-0.41	-0.22	0.33	0.47	0.48	0.55	0.66	0.51	0.41	-0.06	-0.49	0.47	0.44	0.42	0.75	0.09	-0.24	0.03	-0.53	0.33
	Rural 1	-0.54	-0.54	-0.07	-0.04	-0.41	-0.44	-0.42	-0.28	-0.17	-0.14	-0.02	0.06	0.58	0.57	0.50	0.29	0.30	0.04	-0.50	0.32	0.27	-0.05	0.16	-0.18	0.01	0.24	-0.71	0.52
	Rural 2	-0.12	-0.12	-0.44	-0.06	-0.24	-0.18	-0.55	-0.27	-0.34	-0.33	0.05	0.20	0.18	0.34	0.50	0.49	0.30	0.05	-0.23	0.13	0.49	-0.11	0.39	-0.40	-0.12	0.05	-0.30	0.09
	HW1	-0.09	-0.09	-0.38	-0.41	-0.30	-0.52	-0.73	-0.50	-0.59	-0.53	0.10	0.31	0.26	0.36	0.51	0.41	0.53	0.11	-0.26	0.50	0.40	0.18	0.64	-0.18	-0.08	0.16	-0.51	0.09
	MW1	-0.54	-0.54	-0.23	-0.14	-0.24	-0.24	-0.41	-0.14	-0.13	-0.06	0.21	0.30	0.42	0.56	0.73	0.72	0.11	-0.08	-0.50	0.12	0.30	0.16	0.59	-0.17	-0.31	-0.14	-0.38	0.50
	MW2	-0.88	-0.87	-0.30	-0.01	0.06	0.00	0.01	0.23	0.25	0.22	0.22	0.22	0.35	0.46	0.57	0.72	-0.23	-0.22	-0.41	-0.08	-0.01	-0.06	0.33	-0.30	-0.48	-0.35	-0.28	0.85
PN23 raw	RDE	-0.37	-0.37	-0.19	-0.52	-0.17	-0.62	-0.61	-0.47	-0.43	-0.28	0.23	0.35	0.42	0.45	0.55	0.46	0.42	0.01	-0.40	0.55	0.30	0.38	0.73	0.04	-0.14	0.11	-0.60	0.39
	Phase 1	-0.47	-0.47	-0.06	-0.49	0.13	-0.52	-0.32	-0.32	-0.20	-0.03	0.26	0.27	0.30	0.27	0.30	0.29	0.22	-0.06	-0.25	0.45	0.13	0.41	0.56	0.19	-0.16	0.04	-0.47	0.52
	Rural 1	-0.43	-0.42	-0.22	-0.12	-0.35	-0.46	-0.53	-0.34	-0.17	-0.04	0.49	0.63	0.75	0.77	0.76	0.57	0.27	-0.32	-0.72	0.29	0.40	0.08	0.41	-0.15	-0.38	-0.06	-0.62	0.42
	Rural 2	0.21	0.20	-0.36	0.27	0.17	0.13	-0.20	-0.22	-0.10	0.05	0.14	0.14	-0.04	-0.06	-0.08	-0.01	0.14	-0.15	0.11	-0.21	0.64	-0.26	-0.18	-0.23	0.08	0.15	-0.03	-0.21
	HW1	0.43	0.43	-0.23	-0.35	-0.05	-0.45	-0.55	-0.55	-0.53	-0.41	0.10	0.16	0.09	0.05	0.03	-0.08	0.54	0.07	0.00	0.48	0.36	0.01	0.21	-0.13	0.29	0.43	-0.34	-0.38
	MW1	-0.32	-0.32	-0.22	-0.11	-0.30	-0.23	-0.50	-0.24	-0.23	-0.13	0.19	0.31	0.38	0.52	0.69	0.64	0.19	-0.06	-0.46	0.11	0.41	0.15	0.57	-0.16	-0.22	-0.05	-0.33	0.27
	MW2	-0.31	-0.31	-0.39	-0.11	-0.23	-0.21	-0.52	-0.21	-0.27	-0.26	0.07	0.19	0.27	0.45	0.63	0.63	0.23	0.03	-0.34	0.15	0.41	-0.06	0.49	-0.40	-0.16	0.00	-0.36	0.28
PN10 tailpipe	RDE	-0.34	-0.34	-0.10	-0.15	0.61	0.43	0.52	0.68	0.41	0.18	-0.11	-0.25	-0.57	-0.29	-0.01	0.41	-0.60	0.07	0.31	-0.29	-0.57	-0.06	0.25	-0.25	-0.39	-0.61	0.63	0.35
	Phase 1	-0.25	-0.25	-0.57	0.18	0.45	0.56	0.42	0.59	0.33	0.07	-0.16	-0.26	-0.44	-0.28	-0.11	0.35	-0.44	-0.01	0.33	-0.40	-0.29	-0.55	-0.13	-0.66	-0.17	-0.31	0.33	0.25
	Rural 1	-0.28	-0.27	0.02	-0.09	0.75	0.58	0.79	0.83	0.63	0.45	0.08	-0.12	-0.56	-0.37	-0.15	0.32	-0.81	-0.14	0.30	-0.44	-0.75	0.02	0.12	-0.06	-0.48	-0.75	0.81	0.30
	Rural 2	-0.22	-0.23	0.47	-0.37	0.44	0.04	0.32	0.35	0.26	0.18	-0.07	-0.18	-0.41	-0.18	0.03	0.16	-0.39	0.16	0.15	-0.01	-0.47	0.44	0.43	0.32	-0.32	-0.50	0.56	0.24
	HW1	-0.44	-0.44	0.12	-0.35	0.72	0.22	0.51	0.56	0.42	0.31	0.05	-0.13	-0.45	-0.23	0.01	0.37	-0.57	0.00	0.21	-0.13	-0.59	0.23	0.40	0.05	-0.44	-0.62	0.56	0.47
	MW1	-0.55	-0.55	0.05	-0.37	0.50	0.19	0.43	0.54	0.30	0.12	-0.13	-0.22	-0.47	-0.25	0.03	0.39	-0.49	0.15	0.24	-0.08	-0.65	0.31	0.50	0.10	-0.41	-0.58	0.44	0.56
	MW2	-0.49	-0.50	0.43	-0.34	0.36	0.03	0.35	0.36	0.26	0.18	-0.20	-0.29	-0.36	-0.19	0.00	0.15	-0.38	0.23	0.16	-0.01	-0.50	0.49	0.43	0.39	-0.26	-0.43	0.38	0.49
PN23 tail pipe	RDE	-0.47	-0.47	-0.52	0.14	0.42	0.49	0.39	0.62	0.40	0.17	-0.07	-0.19	-0.26	-0.07	0.12	0.56	-0.49	-0.07	0.12	-0.38	-0.30	-0.49	0.00	-0.67	-0.27	-0.38	0.24	0.47
	Phase 1	-0.34	-0.33	-0.52	0.35	0.34	0.59	0.44	0.62	0.45	0.22	-0.07	-0.19	-0.21	-0.08	0.01	0.40	-0.49	-0.13	0.13	-0.49	-0.23	-0.67	-0.28	-0.73	-0.19	-0.30	0.24	0.33
	Rural 1	-0.31	-0.31	0.21	-0.18	0.47	-0.04	0.22	0.12	0.21	0.25	-0.07	-0.25	-0.17	-0.14	-0.13	-0.01	-0.19	0.07	0.13	0.03	-0.13	0.11	0.07	0.11	0.03	-0.04	0.09	0.35
	Rural 2	-0.22	-0.23	0.45	-0.43	0.20	-0.40	-0.11	-0.16	-0.06	0.04	-0.08	-0.19	-0.02	0.05	0.09	0.00	0.07	0.22	-0.05	0.34	-0.04	0.42	0.39	0.33	0.08	0.07	-0.06	0.26
	HW1	-0.13	-0.14	0.27	-0.35	0.39	-0.24	-0.07	-0.07	0.02	0.10	0.06	-0.06	-0.12	0.02	0.11	0.12	-0.03	0.08	0.00	0.18	0.05	0.26	0.35	0.12	-0.08	-0.10	0.13	0.17
	MW1	-0.57	-0.58	-0.04	-0.43	0.46	0.10	0.26	0.43	0.18	0.01	-0.13	-0.19	-0.43	-0.17	0.14	0.48	-0.37	0.19	0.19	0.01	-0.50	0.30	0.61	0.01	-0.41	-0.53	0.34	0.58
	MW2	-0.42	-0.43	0.56	-0.30	0.25	-0.06	0.24	0.22	0.19	0.16	-0.26	-0.35	-0.29	-0.15	-0.01	0.05	-0.27	0.29	0.12	0.03	-0.36	0.53	0.39	0.47	-0.12	-0.27	0.30	0.41
PM tail pipe	RDE	-0.52	-0.51	-0.51	-0.03	0.43	0.44	0.39	0.52	0.33	0.25	0.23	0.19	-0.21	-0.11	0.12	0.59	-0.49	-0.26	0.09	-0.35	-0.31	0.00	0.30	-0.20	-0.53	-0.58	0.27	0.50

Table 16.3 Mapping of significant fuel correlations for PN uncorrected emission with a threshold of 0.6 (abs)

Correlation map, uncorrected, threshold of 0.6 (abs)		RON	MON	Density	IBP	5	10	20	30	40	50	60	70	80	90	95	FBP	E70	E100	E150	DVPE	Olefins	Aromatics	C9 and C9+ aro	<C9 Aromatics	Oxygen	Ethanol	ETBE	MTBE
						(Vol %)																	(%v/v)			(%m/m)	(%v/v)		
PN10 raw	RDE														-0.72	-0.74				0.67									
	Phase 1										-0.71	-0.74							0.84										
	Rural 1																												
	Rural 2																												
	HW1																												
	MW1																												
	MW2																												
PN23 raw	RDE				-0.73		-0.78			-0.86	-0.86							0.76	0.79		0.86		0.77						
	Phase 1									-0.68	-0.72	-0.75	-0.64					0.64	0.80							0.71	0.72		
	Rural 1						-0.65	-0.69																0.67					
	Rural 2																							0.69					
	HW1				-0.77																			0.86					
	MW1				-0.76		-0.70			-0.74	-0.74										0.76			0.86					
	MW2				-0.78		-0.82	-0.74		-0.82	-0.77							0.71			0.84		0.75	0.83					
PN10 tailpipe	RDE				0.75		0.82			0.70	0.66								-0.67		-0.82			-0.66					
	Phase 1																							0.61					
	Rural 1																			-0.61									
	Rural 2					-0.62								0.76	0.75	0.65				-0.80									
	HW1					-0.60									0.68	0.68				-0.70									
	MW1																											0.64	
	MW2		0.61																										
PN23 tail pipe	RDE																												
	Phase 1							-0.68																					
	Rural 1							-0.61																					
	Rural 2							-0.67																					
	HW1							-0.67																					
	MW1																												
	MW2							-0.68		-0.62	-0.62																		
PM tail pipe	RDE						0.74		0.66														-0.72		-0.72				
PN10 raw	RDE						**-0.65**																**0.65**	**0.60**					
	Phase 1											-0.74	-0.69						0.74							0.73	0.71		
	Rural 1						-0.64		-0.63														0.68		0.69				
	Rural 2																						0.74	0.63	0.60				
	HW1				-0.69		-0.67														0.64		0.67	0.69					
	MW1						-0.94	-0.88	-0.91	-0.88								0.88			0.88							-0.73	
	MW2					-0.77	-0.85	-0.87	-0.87	-0.75								0.85			0.70							-0.69	
PN23 raw	RDE						**-0.74**																**0.84**	**0.69**	**0.69**				
	Phase 1						-0.76		-0.67	-0.71	-0.63							0.71	0.62		0.74		0.74		0.73			-0.66	
	Rural 1						-0.75		-0.72														0.81		0.78				
	Rural 2																						0.86		0.73				
	HW1				-0.79		-0.85														0.81		0.89	0.78					
	MW1						-0.95	-0.88	-0.92	-0.91	-0.76							0.92			0.89							-0.77	
	MW2						-0.85	-0.84	-0.86	-0.83	-0.72							0.87			0.74							-0.70	
PN10 tailpipe	RDE						**-0.94**	**-0.85**	**-0.88**	**-0.89**	**-0.74**							**0.87**			**0.88**		**0.78**					**-0.70**	
	Phase 1											-0.61	-0.63	-0.67	-0.78	-0.77				0.75		-0.70							
	Rural 1						-0.93	-0.86	-0.90	-0.83								0.84			0.81		0.80		0.68				
	Rural 2						-0.68		-0.70	-0.61								0.64	0.62				0.67		0.70		0.62		
	HW1						-0.94	-0.86	-0.92	-0.86								0.88			0.84		0.78						
	MW1						-0.95	-0.90	-0.91	-0.96	-0.84							0.94			0.93								
	MW2						-0.84	-0.86	-0.82	-0.81	-0.72							0.85			0.74							-0.75	
PN23 tail pipe	RDE						**-0.93**	**-0.86**	**-0.88**	**-0.90**	**-0.75**							**0.89**			**0.87**		**0.74**					**-0.75**	
	Phase 1											-0.62	-0.67		-0.72	-0.78				0.69		-0.61							
	Rural 1						-0.93	-0.89	-0.92	-0.85								0.88			0.81		0.75					-0.74	
	Rural 2						-0.80	-0.63	-0.72	-0.67								0.70	0.71		0.72		0.73		0.70		0.65		
	HW1						-0.95	-0.87	-0.93	-0.87								0.89			0.85		0.76					-0.72	
	MW1						-0.95	-0.90	-0.91	-0.96	-0.84							0.94			0.92								
	MW2						-0.84	-0.85	-0.82	-0.82	-0.73							0.85			0.74							-0.74	
PM tail pipe	RDE																												
PN10 raw	RDE							-0.72								0.67								0.69					
	Phase 1						-0.66	-0.77								0.61								0.72					
	Rural 1	-0.79	-0.80																									-0.71	0.78
	Rural 2																												
	HW1							-0.68																0.63					
	MW1															0.72	0.74												
	MW2	-0.83	-0.83														0.74												0.81
PN23 raw	RDE							-0.60																0.70					
	Phase 1				-0.61																0.60								
	Rural 1													0.68	0.72	0.75	0.63			-0.66									
	Rural 2																												
	HW1																												
	MW1	-0.73	-0.73													0.61	0.72							0.61					0.70
	MW2															0.61													
PN10 tailpipe	RDE																												
	Phase 1			-0.63																					-0.65				
	Rural 1					0.75		0.79	0.84									-0.80				-0.79					-0.74	0.79	
	Rural 2																												
	HW1	-0.61				0.70																					-0.66		0.63
	MW1	-0.74	-0.74																								-0.61		0.74
	MW2																												
PN23 tail pipe	RDE			-0.62																					-0.63				
	Phase 1																						-0.64		-0.69				
	Rural 1																												0.61
	Rural 2																												
	HW1																												
	MW1	-0.65	-0.65																					0.60					0.65
	MW2																												
PM tail pipe	RDE																												

Table 16.4 Mapping of significant fuel correlations for PN corrected emission with a threshold of 0.6

Correlation map, corrected, threshold of 0.6 (abs)		RON	MON	Density	IBP	5	10	20	30	40	50	60	70	80	90	95	FBP	E70	E100	E150	DVPE	Olefins	Aromatics	C9 and C9+ aro	<C9 Aromatics	Oxygen	Ethanol	ETBE	MTBE
						(Vol %)																	(%v/v)			(%m/m)	(%v/v)		
PN10 raw	RDE				-0.66						-0.63																		
	Phase 1										-0.68	-0.71							0.78										
	Rural 1																												
	Rural 2																												
	HW1																												
	MW1																												
	MW2																												
PN23 raw	RDE				-0.74		-0.79			-0.88	-0.87							0.77	0.76		0.86		0.76						
	Phase 1									-0.63	-0.72	-0.76	-0.67						0.79							0.68	0.64		
	Rural 1																												
	Rural 2																							0.67					
	HW1				-0.70																			0.75					
	MW1				-0.74					-0.64	-0.70										0.70			0.78					
	MW2				-0.76		-0.74			-0.75	-0.75								0.65		0.80		0.69	0.79					
PN10 tailpipe	RDE				0.74						0.65			0.66					-0.70	-0.65									
	Phase 1																												
	Rural 1																												
	Rural 2					-0.61								0.68	0.72	0.68				-0.75									
	HW1															0.63													
	MW1																											0.64	
	MW2				-0.76		-0.74			-0.75	-0.75								0.65		0.80		0.69	0.79					
PN23 tail pipe	RDE																												
	Phase 1																												
	Rural 1																												
	Rural 2																												
	HW1			-0.67																									
	MW1				-0.71																			0.62					
	MW2																							0.81					
PM tail pipe	RDE																						-0.73		-0.73				
PN10 raw	RDE						**-0.74**														**0.61**		**0.77**	**0.71**				**-0.62**	
	Phase 1						-0.64		-0.66	-0.78	-0.76	-0.69					####	0.76	0.73		0.70				0.65	0.64	0.73		
	Rural 1						-0.64		-0.63														0.68		0.68				
	Rural 2																						0.77	0.64	0.63				
	HW1				-0.67		-0.65														0.61		0.67	0.67					
	MW1						-0.94	-0.88	-0.91	-0.89								0.89			0.89							-0.72	
	MW2					-0.76	-0.83	-0.85	-0.83	-0.74								0.83			0.68							-0.68	
PN23 raw	RDE						**-0.75**																**0.84**		**0.72**				
	Phase 1					-0.61	-0.72		-0.69	-0.72	-0.65							0.73			0.69		0.69		0.72			-0.67	
	Rural 1						-0.73		-0.71														0.80		0.77				
	Rural 2																						0.87		0.75				
	HW1				-0.78		-0.86														0.82		0.87	0.76	0.70				
	MW1						-0.96	-0.88	-0.93	-0.90	-0.73							0.91			0.89							-0.77	
	MW2						-0.84	-0.82	-0.83	-0.81	-0.71							0.85			0.73							-0.69	
PN10 tailpipe	RDE						**-0.94**	**-0.85**	**-0.88**	**-0.89**	**-0.74**							**0.87**			**0.88**		**0.78**						
	Phase 1											-0.65	-0.66	-0.67	-0.76	-0.74				0.74		-0.72							
	Rural 1						-0.93	-0.86	-0.90	-0.83								0.84			0.82		0.80		0.68				
	Rural 2						-0.68		-0.69									0.63	0.63				0.67		0.69		0.63		
	HW1						-0.95	-0.86	-0.92	-0.86								0.87			0.86		0.79						
	MW1						-0.96	-0.90	-0.91	-0.95	-0.82							0.93			0.93								
	MW2						-0.83	-0.85	-0.82	-0.82	-0.74							0.85			0.74							-0.73	
PN23 tail pipe	RDE						**-0.93**	**-0.86**	**-0.89**	**-0.90**	**-0.75**							**0.89**			**0.87**		**0.73**					**-0.74**	
	Phase 1											-0.68	-0.71	-0.63	-0.74	-0.77				0.71		-0.64							
	Rural 1						-0.94	-0.89	-0.93	-0.85								0.88			0.81		0.75					-0.74	
	Rural 2						-0.80	-0.63	-0.71	-0.67								0.70	0.71		0.71		0.72		0.70		0.65		
	HW1						-0.96	-0.86	-0.93	-0.87								0.89			0.86		0.77					-0.72	
	MW1						-0.96	-0.90	-0.92	-0.95	-0.82							0.94			0.93								
	MW2						-0.83	-0.84	-0.81	-0.82	-0.75							0.85			0.74							-0.72	
PM tail pipe	RDE																												
PN10 raw	RDE							-0.68								0.70								0.69					
	Phase 1						-0.60	-0.67								0.66								0.75					
	Rural 1																											-0.71	
	Rural 2																												
	HW1							-0.73																0.64					
	MW1															0.73	0.72												
	MW2	-0.88	-0.87														0.72												0.85
PN23 raw	RDE						-0.62	-0.61																0.73					
	Phase 1																												
	Rural 1												0.63	0.75	0.77	0.76				-0.72								-0.62	
	Rural 2																					0.64							
	HW1																												
	MW1															0.69	0.64												
	MW2															0.63	0.63												
PN10 tailpipe	RDE					0.61			0.68																		-0.61	0.63	
	Phase 1																								-0.66				
	Rural 1					0.75		0.79	0.83									-0.81				-0.75					-0.75	0.81	
	Rural 2																												
	HW1					0.72																					-0.62		
	MW1																					-0.65							
	MW2																												
PN23 tail pipe	RDE								0.62																-0.67				
	Phase 1								0.62														-0.67		-0.73				
	Rural 1																												
	Rural 2																												
	HW1																												
	MW1																							0.61					
	MW2																												
PM tail pipe	RDE																												

16.3. EFFECT OF FUEL PROPERTIES ON PN EMISSIONS

The effect of the declared fuel properties was further analysed according to its influence on PN emission trends. If the correlation coefficient was found positive, an increment in the given fuel property would typically increase the corresponding PN emissions and vice versa. The main findings of the effect of different fuel properties are presented in ***Table 16.5***. Based on the results, some outliners were concluded: Fuels with higher content of aromatics and with higher vapour pressure (DVPE) tend to increase PN emissions (applies for GDI vehicles), while fuels with a low yield in the lighter part of the distillation curve (IBP to 50% vol) tend to decrease PN emissions. The effect of low boiling point is confirmed by the trends obtained for fuel E70 value, which in turn had an opposite, increasing effect on PN formation. Examples of the effect of aromatics and fuel 10 % vol properties are shown in ***Figure 16.1*** and ***Figure 16.2***. Strongest correlation between fuel properties and PN emissions were found for Vehicle B with r-values up to 0.9. The fuel response between all test vehicles were found somewhat unequal. Generally poorest correlation (within the defined limits) between fuel properties and PN emissions were found for the vehicle with PFI-technology, vehicle C, and thus no correlation values above 0.8 (abs) was found. The GDI engines (Vehicles A and B) were found more sensitive for content of total aromatics while the PN EO emissions of the PFI equipped vehicle (Vehicle C) were dependent solely on ≥ C9 aromatics. Another common finding was that the fuel properties in the early yield had a greater effect than the latter part of the distillation curve. Furthermore, TP emissions were not necessarily in line with PN EO emissions as the TWC and particulate filter influence strongly on the PN behaviour. For example, while PN_{10} and PN_{23} EO emissions for vehicle A decrease as a function of early yield, the TP emission trend was seen increasing. For some parameters such as ethanol and ETBE with vehicle C, no correlation between EO and TP emissions could be found.

Table 16.5 Fuel property effect on PN EO and PN TP emission over total RDE test for all vehicles.

		IBP	5% vol	10% vol	20% vol	30% vol	40% vol	50% vol	80% vol	90% vol	95% vol	FBP	E70	E100	E150	DVPE	Aromatics (%v/v)	C9 and C9+ aromatics (% v/v)	<C9 Aromatics	Ethanol (%v/v)	ETBE (%v/v)
Vehicle A, Corrected	PN10 EO	-0.7						-0.6													
	PN23 EO	-0.7		-0.8			-0.9	-0.9					0.8	0.8		0.9	0.8				
	PN10 TP	0.7						0.7	0.7					-0.7	-0.7						
	PN23 TP																				
Vehicle B, Uncorrected	PN10 EO			-0.7													0.7	0.6			
	PN23 EO			-0.7													0.8	0.7	0.7		
	PN10 TP			-0.9	-0.8	-0.9	-0.9	-0.7					0.9			0.9	0.8				-0.7
	PN23 TP			-0.9	-0.9	-0.9	-0.9	-0.8					0.9			0.9	0.7				-0.7
Vehicle B, Corrected	PN10 EO			-0.7												0.6	0.8	0.7			-0.6
	PN23 EO			-0.8													0.8		0.7		
	PN10 TP			-0.9	-0.8	-0.9	-0.9	-0.7					0.9			0.9	0.8				
	PN23 TP			-0.9	-0.9	-0.9	-0.9	-0.7					0.9			0.9	0.7				-0.7
Vehicle C, Corrected	PN10 EO				-0.7						0.7							0.7			
	PN23 EO			-0.6	-0.6													0.7			
	PN10 TP		0.6			0.7														-0.6	0.6
	PN23 TP					0.6													-0.7		

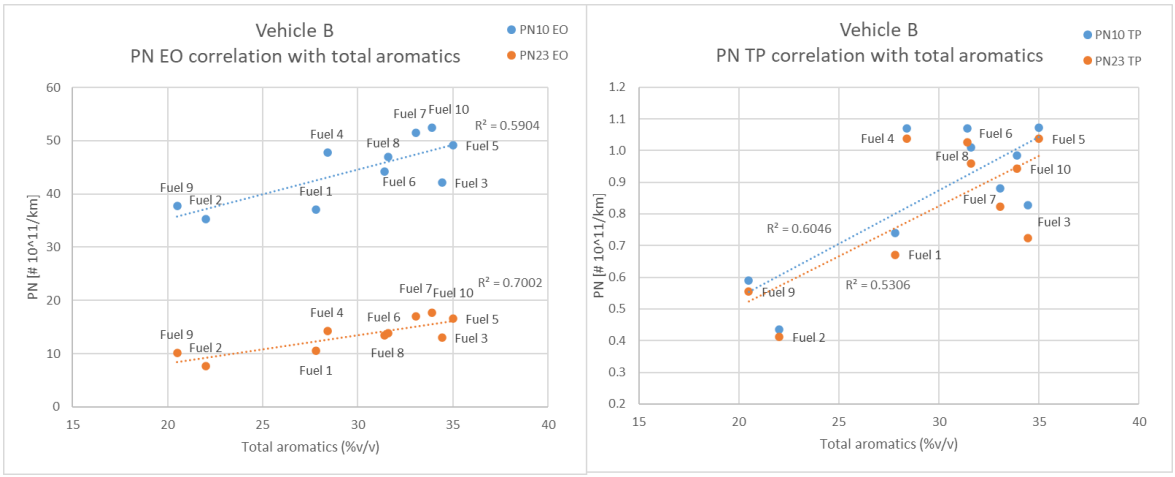


Figure 16.1 Examples of the correlation between PN emissions (EO and TP) and aromatics for vehicle B

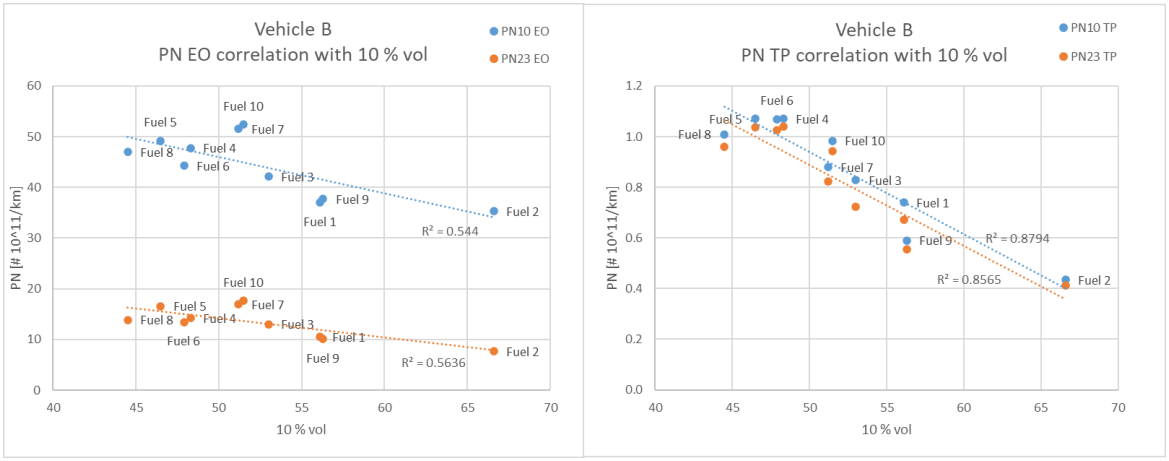


Figure 16.2 Correlation between PN emissions (EO and TP) and 10 % yield for vehicle B

Figure 16.3, ***Figure 16.4*** and ***Figure 16.5*** illustrate the fuel response of each test vehicle in respect to the sampled PN emissions. The figures represent a relative change for PN emissions in respect to corresponding average PN results calculated from all fuels. For vehicle A, the fuel response was found somewhat contradictory. Several cases were found where a fuel simultaneously reduced PN EO emissions, but increased PN TP emissions. This effect was as seen e.g., for fuels 2, 4, 8, 9 and 10. Furthermore, the relative fuel effect seemed to vary in respect of PN_{10} and PN_{23} emissions case by case. The same phenomenon was not seen for vehicle B, as the fuel effect was more stringent for the whole sampled PN spectrum. The fuel effect on all PN emission types were found relatively comparable and the fuel influence (direction) for each individual fuel was equal. The fuel effect was slightly higher for TP emissions than EO emissions.

The influence of fuel response for vehicle C was found somewhere in between vehicle A and B. The fuel effect for PN emissions were mostly stringent with the PN EO and TP trends remaining generally coaxial. Opposite to vehicle B, the fuel effect for vehicle C was found higher for PN EO than for PN TP emissions. ***Figure 16.6***

indicate that the fuel effect for the test vehicles is not directly comparable. The fuel effect between the test vehicles seemed sometimes relatively random both in terms of magnitude of effect and direction. For example, the fuel effect for vehicles A and B were mostly opposite in terms of PN TP emissions. However, the response of PN_{23} EO emissions were mostly similar. This finding suggests that even engines with similar fuel injection technologies may respond unequal on any changes in fuel properties because the properties of the applied GPF has a remarkable influence for the tail-pipe emissions. The study also demonstrated that the tail-pipe particulate emissions for modern gasoline vehicles equipped with GPFs, especially for this case seen with vehicle A, are typically extremely low.

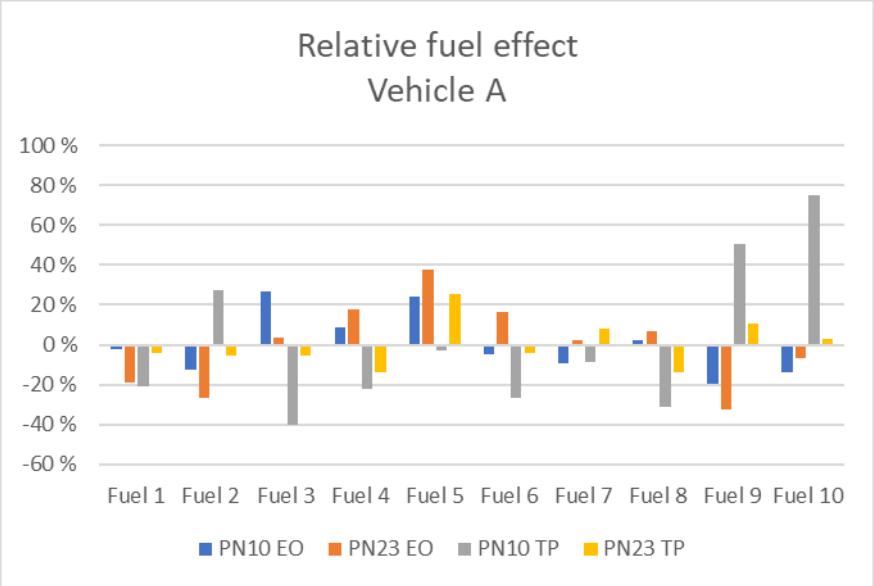


Figure 16.3 The relative effect of the test fuels for vehicle A in relation to calculated average PN

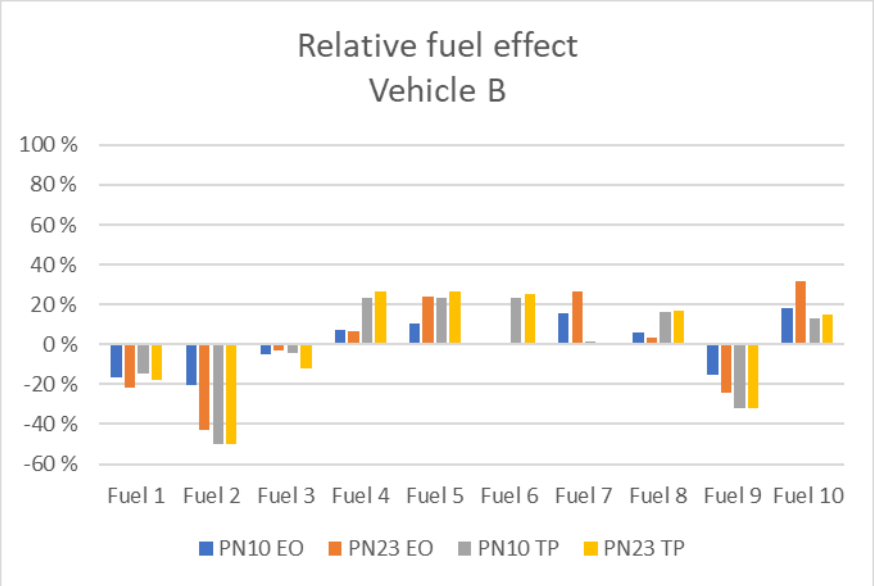


Figure 16.4 The relative effect of the test fuels for vehicle B in relation to calculated average PN

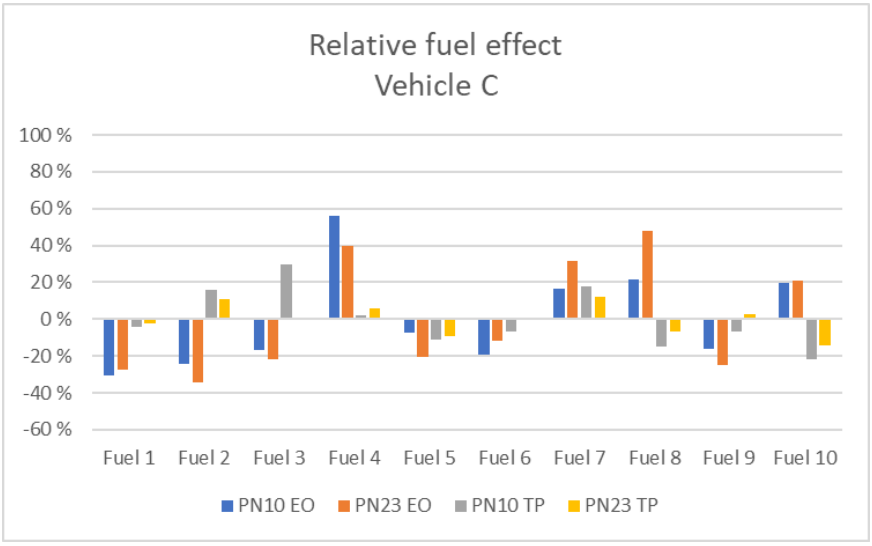


Figure 16.5 The relative effect of the test fuels for vehicle C in relation to calculated average PN

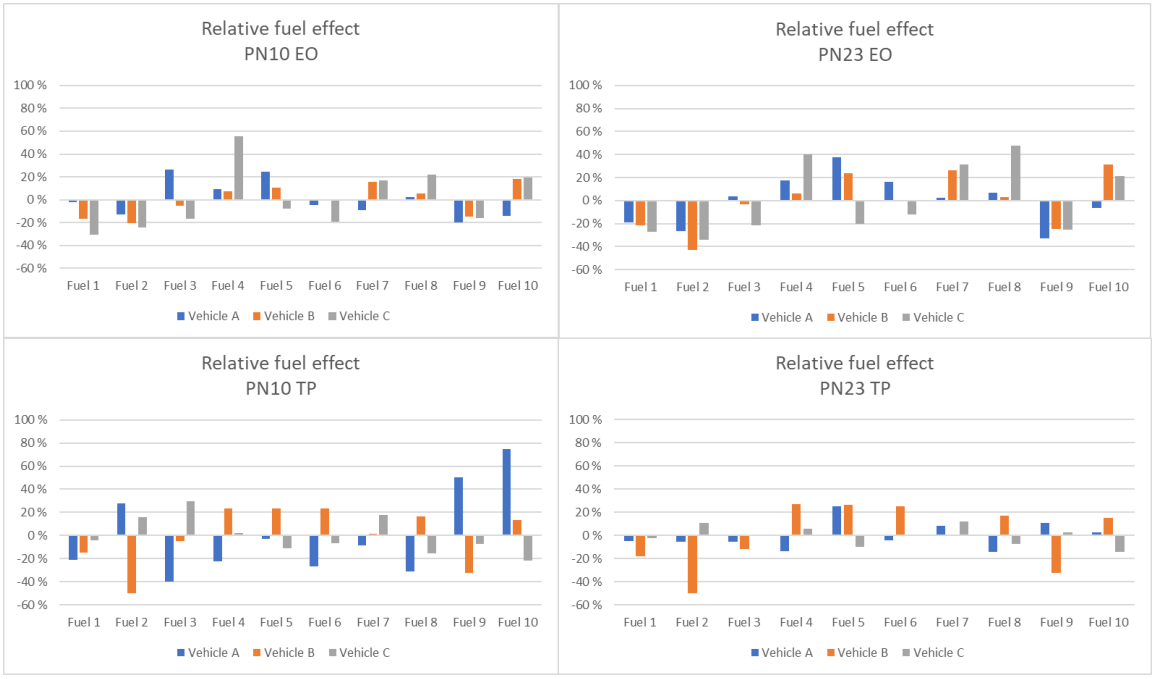


Figure 16.6 A comparison of fuel response for PN emissions between all test vehicles

17. PHASE 2 - PN MODELING

17.1. AN OVERVIEW OF PN MODELLING METHODS

First, based on the excel correlation table, significant input parameters or predictor variables were defined for each response variable (PN10_EO, PN23_EO, PN10_TP, PN23_TP). The input predictor variables used in this study were the same that were defined previously. Initially, a linear regression method was used by fitting the linear regression model considering all the predictor variables as per emission type. The linear regression model was produced in MATLAB. By default, MATLAB fits the linear regression model based on Ordinary least square method. The linear regression model produces an equation with estimates (constants) for corresponding input variables including an intercept, as shown in an example in ***Figure 17.1***. The equation formed is a typical linear model equation in form of $y = C + a * x_1 + b * x_2 + c * x_3$ etc.

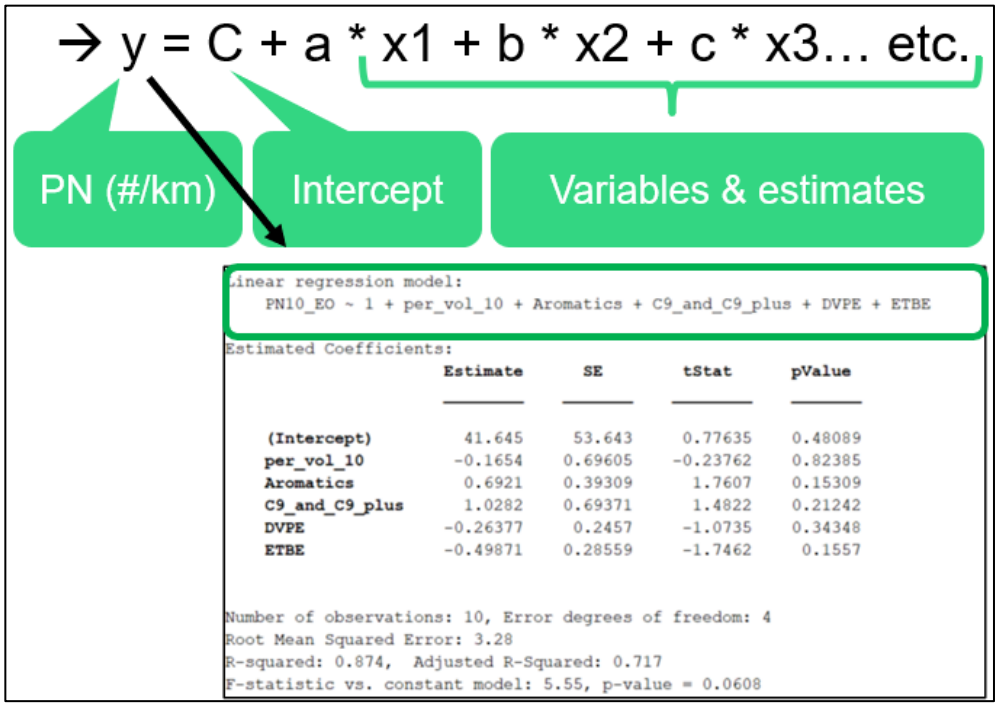


Figure 17.1 An example of the equation obtained from the MATLAB linear multi variable model

Further, a step wise regression model was applied. It creates a linear regression model by adding or removing predictors, starting from a constant model. It uses forward and backward stepwise regression to determine the final model. At each step, the elimination method searches for terms to add to the model or to remove from the model based on the defined criteria (shown in ***Figure 17.2***). At each step, the method checks whether any term (predictor) is redundant (linearly dependent) with other terms in the current model or not. If any term is linearly dependent with other terms in the current model, it removes the redundant term.

In simple terms, selection criteria for the predictor variables are based on p-value. p-value for an F-test of the change in the sum of squared error that results from adding or removing the term. A selection criterion for the predictor was used

following: **If the p value of the F-statistics is less than 0.05**, add the term in the model.

```
1. Removing per_vol_10, FStat = 0.056466, pValue = 0.82385
2. Removing DVPE, FStat = 2.5368, pValue = 0.1721
3. Removing C9_and_C9_plus, FStat = 1.0976, pValue = 0.33514

mdl1_PN10_EO_step1 =


Linear regression model:
    PN10_EO ~ 1 + Aromatics + ETBE

Estimated Coefficients:
                   Estimate       SE        tStat       pValue
                   ________    ________    ________    _________

    (Intercept)      23.227      7.1135      3.2652     0.013766
    Aromatics        0.7788     0.22643      3.4394     0.010846
    ETBE            -0.37451    0.15834     -2.3652      0.04996


Number of observations: 10, Error degrees of freedom: 7
Root Mean Squared Error: 3.33
R-squared: 0.772,  Adjusted R-Squared: 0.707
F-statistic vs. constant model: 11.9, p-value = 0.00563
```

Figure 17.2 An example of the forward and backward stepwise regression method

The methods for stepwise linear model may be expressed as follows:

Step 1. Fit the initial model (based on predictor variables chosen in MS Excel).

Step 2. Examine a set of available terms not in the model. If any of the terms have p-values less than an entrance tolerance ((that is, if it is unlikely that a term would have a zero coefficient if added to the model), in this study it is p=0.05, add the term with the smallest p-value and repeat this step; otherwise, go to step 3.

Step 3. If any of the available terms in the model have p-values greater than an exit tolerance (that is, the hypothesis of a zero coefficient cannot be rejected), in this study p=0.1, remove the term with the largest p-value and return to step 2; otherwise, end the process.

At any stage, the function will not add a higher-order term if the model does not also include all lower-order terms that are subsets of the higher-order term. For example, the function will not try to add the term X1:X2^2 unless both X1 and X2^2 are already in the model. Similarly, the function will not remove lower-order terms that are subsets of higher-order terms that remain in the model. For example, the function will not try to remove X1 or X2^2 if X1:X2^2 remains in the model. This method was used for all the cases defined previously.

When the final models were formed, the model robustness for each vehicle was tested against the models specifically created for the other vehicles. Additionally, the models created were compared against the model from the previous project. This model was distributed by Concawe. Because the PN response and the magnitude of PN emissions differed from vehicle to vehicle, a general model was

created. This model accounted for relative changes in PN emissions as a response to changes in fuel characteristics. To implement this type of model, the baseline PN emissions and fuel attributes for the baseline result for the modelled vehicle must be known.

The model fuel effect, errors and uncertainties were calculated stepwise using the following method:

- Measured error: pure error (noise) was calculated from average standard deviation for each vehicle
- Fuel effect: Measured values – pure error
- Lack of fit: Fuel effect * modelled R^2

17.2. OPTIMIZATION OF INPUT DATA

The stepwise elimination determined the variables that were used in the final model. The influence of the stepwise elimination on the modelling results were first analysed by comparing the effect on main model key performance indicators, such as coefficient of determination (R^2), RMSE and P-value. The starting point for variables included in the initial models are shown in Table 17.2. ***Table 17.4*** shows the key performance indicators (R^2, P-value and RMSE) for each model. Correspondingly, final variables for the models after the stepwise elimination are shown in Table 17.3 and its key performance indicators in ***Table 17.5***. The changes in key performance indicators are shown in ***Table 17.6***. Initially, the quantity of variables included in each model varied between 1 to 5 variables. The elimination process typically reduced the variable count to either 1 or 2 variables in total. One exception was PN10 for Vehicle C, which oppositely introduced a new estimate (90 %vol * 95 %vol), increasing the quantity of variables from 4 to 5.

The advantage of stepwise elimination is to reduce the redundant terms and thus avoids any risk of overfitting. The selection criteria for each predictor variable were a P-value less than 0.05. However, due to the reduction of predictor variables negative effect on the coefficient of determination was expected. A stepwise model with a low P-value is robust and statistically stable, hence this was seen as a more important factor than solely optimizing the R^2. The improvement for each model may also be seen as a general reduction in RMSE. To illustrate the effect of change in the key performance indicators were defined as described in ***Table 17.1***. The final summarizing table of the changes are illustrated in ***Table 17.7***.

Table 17.1 The effect of change in model key performance indicators

R^2		P-value		RMSE	
> 0.01	+	> 0.01	-	> 0.01	-
0.01 > - 0.01	o	0.01 > - 0.01	o	0.01 > - 0.01	o
> -0.05	-	> -0.05	+	< -0.01	+
> -0.1	--	> -0.1	++	< -0.5	++
< -0.1	---	< -0.1	+++	< -1	+++

Table 17.2 The initial variables determined based on the fuel correlation mapping

Initial model variables	Emision type	x1	x2	x3	x4	x5	Num of variables
Vehicle A, corrected	PN10 EO	IBP	50% vol				2
	PN23 EO	IBP	E70	E100	DVPE	Aromatics	5
	PN10 TP	IBP	50% vol	80% vol	E100	E150	5
	PN23 TP	NA	NA	NA	NA	NA	0
Vehicle B, uncorrected	PN10 EO	10 % vol	Aromatics	C9 and C9+ aro			3
	PN23 EO	10 % vol	Aromatics	C9 and C9+ aro	<C9 Aromatics		4
	PN10 TP	E70	DVPE	Aromatics	ETBE		4
	PN23 TP	E70	DVPE	Aromatics	ETBE		4
Vehicle B, corrected	PN10 EO	10 % vol	DVPE	Aromatics	C9 and C9+ aro	ETBE	5
	PN23 EO	10 % vol	Aromatics	<C9 Aromatics			3
	PN10 TP	E70	DVPE	Aromatics			3
	PN23 TP	E70	DVPE	Aromatics	ETBE		4
Vehicle C, uncorrected	PN10 EO	20%vol	95% vol	C9 and C9+ aro			3
	PN23 EO	10%vol	20%vol	C9 and C9+ aro			3
	PN10 TP	30% vol	Ethanol	ETBE			3
	PN23 TP	30% vol	<C9 Aromatics				2

Table 17.3 The variables of the final models selected by the stepwise elimination

Final variables	Emision type	x1	x2	x3	x4	x5	Num of variables
Vehicle A, corrected	PN10 EO	IBP					1
	PN23 EO	E70	Aromatics				2
	PN10 TP	IBP					1
	PN23 TP						0
Vehicle B, uncorrected	PN10 EO	per_vol_10					1
	PN23 EO	C9_and_C9_plus	<C9_aromatics				2
	PN10 TP	Aromatics	E70				2
	PN23 TP	Aromatics	E70				2
Vehicle B, corrected	PN10 EO	Aromatics	ETBE				2
	PN23 EO	Aromatics					1
	PN10 TP	Aromatics	E70				2
	PN23 TP	Aromatics	E70				2
Vehicle C, uncorrected	PN10 EO	-- 20% vol	-- 95% vol	C9 and C9+ aro (% v/v)	20% vol * C9 and C9+ aro		4
	PN23 EO	C9_and_C9_plus					1
	PN10 TP	per_vol_30					1
	PN23 TP	<C9_aromatics					1

Table 17.4 Model evaluation of the initial models and their variables

Initial model variables		Num. Of initial variables	R^2	P-value	RMSE
Vehicle A	PN10 EO	2	0.49	0.092	7.04
	PN23 EO	5	0.87	0.070	0.43
	PN10 TP	5	0.73	0.243	0.01
	PN23 TP	0	NA	NA	NA
Vehicle B, uncorrected	PN10 EO	3	0.52	0.194	7.69
	PN23 EO	4	0.75	0.030	2.12
	PN10 TP	4	0.96	0.001	0.61
	PN23 TP	4	0.94	0.003	0.07
Vehicle B, corrected	PN10 EO	5	0.87	0.060	3.28
	PN23 EO	3	0.75	0.029	1.96
	PN10 TP	3	0.92	0.000	0.06
	PN23 TP	4	0.94	0.003	0.07
Vehicle C	PN10 EO	3	0.84	0.008	2.45
	PN23 EO	3	0.64	0.089	1.05
	PN10 TP	3	0.50	0.213	0.01
	PN23 TP	2	0.56	0.055	0.00

Table 17.5 Model evaluation of the final models with reduced variables

Final variables		Num. of variables	R^2	P-value	RMSE
Vehicle A	PN10 EO	1	0.43	0.039	6.98
	PN23 EO	2	0.80	0.004	0.40
	PN10 TP	1	0.54	0.015	0.01
	PN23 TP	0	NA	NA	NA
Vehicle B, uncorrected	PN10 EO	1	0.43	0.041	7.28
	PN23 EO	2	0.71	0.013	2.11
	PN10 TP	2	0.95	0.000	0.06
	PN23 TP	2	0.93	0.000	0.07
Vehicle B, corrected	PN10 EO	2	0.77	0.006	3.33
	PN23 EO	1	0.70	0.003	1.87
	PN10 TP	2	0.94	0.000	0.06
	PN23 TP	2	0.93	0.000	0.07
Vehicle C	PN10 EO	4	0.94	0.002	1.59
	PN23 EO	1	0.53	0.017	1.03
	PN10 TP	1	0.46	0.030	0.01
	PN23 TP	1	0.45	0.034	0.00

Table 17.6 The effect of variable reduction on R^2 and P-value

Model evaluation		Change in variable count	R^2	P-value	RMSE
Vehicle A	PN10 EO	-1	-0.06	-0.05	-0.06
	PN23 EO	-3	-0.06	-0.07	-0.04
	PN10 TP	-4	-0.19	-0.23	0.00
	PN23 TP	0			
Vehicle B, uncorrected	PN10 EO	-2	-0.09	-0.15	-0.41
	PN23 EO	-2	-0.04	-0.02	-0.01
	PN10 TP	-2	-0.01	0.00	-0.56
	PN23 TP	-2	-0.02	0.00	0.00
Vehicle B, corrected	PN10 EO	-3	-0.10	-0.05	0.05
	PN23 EO	-2	-0.05	-0.03	-0.09
	PN10 TP	-1	0.03	0.00	0.00
	PN23 TP	-2	-0.01	0.00	0.00
Vehicle C	PN10 EO	1	0.10	-0.01	-0.86
	PN23 EO	-2	-0.11	-0.07	-0.02
	PN10 TP	-2	-0.04	-0.18	0.00
	PN23 TP	-1	-0.12	-0.02	0.00

Table 17.7 Evaluation of the gains and losses obtained by variable reduction

Model evaluation		Total number of variables	R^2	P-value	RMSE
Vehicle A	PN10 EO	1	--	++	+
	PN23 EO	2	--	++	+
	PN10 TP	1	---	+++	o
	PN23 TP				o
Vehicle B, uncorrected	PN10 EO	1	--	+++	+
	PN23 EO	2	-	+	+
	PN10 TP	2	o	o	++
	PN23 TP	2	-	o	o
Vehicle B, corrected	PN10 EO	2	---	++	-
	PN23 EO	1	--	+	+
	PN10 TP	2	+	o	o
	PN23 TP	2	-	o	o
Vehicle C	PN10 EO	4	+	o	++
	PN23 EO	1	---	++	+
	PN10 TP	1	-	+++	o
	PN23 TP	1	---	+	o

17.3. MODELLING RESULTS

This chapter presents in depth the final models created by MATLAB. As described previously, each model contains an intercept (offset determining constant) and a set of estimates (constant * fuel property), which describe the slope of each model. The vehicle specific equations are furthermore presented for each data set (and vehicle) in terms of equation, significance (P-value) of each variable and total equation and finally as a comparison to the obtained experimental results. The significance of each variable and total model equation was ranked between o to *** depending on the obtained P-value according to Table 17.8.

Table 17.8 Ranking and symbol for the significance

Significance	
< 0.001	***
< 0.01	**
< 0.05	*
> 0.05	o

The modelling accuracy was defined by considering any uncertainties suffered from both the experimental and modelling work. The uncertainties were defined as pure error (experimental uncertainty) and lack of fit (modelling uncertainty).

Experimentally defined fuel effect was determined solely based on the experimental uncertainties. The accuracy of each model was therefore a result of all these three factors combined, which were defined as follows:

Pure error (%) = average standard deviation of the PN results obtained from all fuels per vehicle

Fuel effect (%) = 1 – pure error (%)

Lack of fit (%) = (1 – modelling R^2) * fuel effect (%)

Modelling accuracy (%) = 1 – (pure error + lack of fit)

17.3.1. Vehicle A

The final equations for vehicle A (corrected) models were as follows:

PN10 EO = C + a * x1 = 105.65 + -1.5287 * IBP
with an error obtained from the experimental data of ± 18 %

PN23 EO = C + a *x1 + b * x2 = 0.072 + 0.03903 * E70 + 0.078263 * Aromatics
with an error obtained from the experimental data of ± 19 %

PN10 TP = C + a *x1 = -0.030277 + 0.0015494 * IBP
with an error obtained from the experimental data of ± 36 %

PN23 TP = No feasible equation available

A summary of the created PN models for Vehicle A (corrected) is presented in ***Table 17.9***. Due to the low correlation between PN_{23} TP emissions and any fuel properties, no feasible equation for PN_{23} TP was created.

Table 17.9 A summary describing the variables in their influence used for Vehicle A (with corrected values)

Vehicle A model summary, variables and their significance												
PN10 EO				PN23 EO				PN10 TP				PN23 TP
Variables	Constant	P-value	Significance	Variables	Constant	P-value	Significance	Variables	Constant	P-value	Significance	
Intercept	105.7	0.0009	***	Intercept	0.072	0.929	o	Intercept	-0.030	0.1071	o	
IBP	-1.5	0.0394	*	E70	0.033	0.025	*	IBP	0.002	0.0154	*	
				Aromatics	0.078	0.031	*					
Total		0.0394	*	Total		0.0036	**	Total		0.0154	*	

Figure 17.3 illustrates the share of the main uncertainties determined for each vehicle A model. Despite the fuel effect was found strong for PN_{10} EO, the model suffered from a significant lack of fit. This was suspected to be a result of the strong non-linear PN_{10} EO behaviour from the experimental part, which was strongly influenced by the correction. Any model for the corresponding emissions based on the uncorrected values was found even less significant, thus demonstrates the main challenges for modelling data sets with severe, non-linear trends. Highest model accuracy for any vehicle A related model was obtained for PN_{23} EO, which in turn suffered less from similar trend effects, yet resulting in overall a relatively confident model. Similarly, considering the noise contribution for PN_{10} TP data, the share of lack of fit was overall concluded as relatively low.

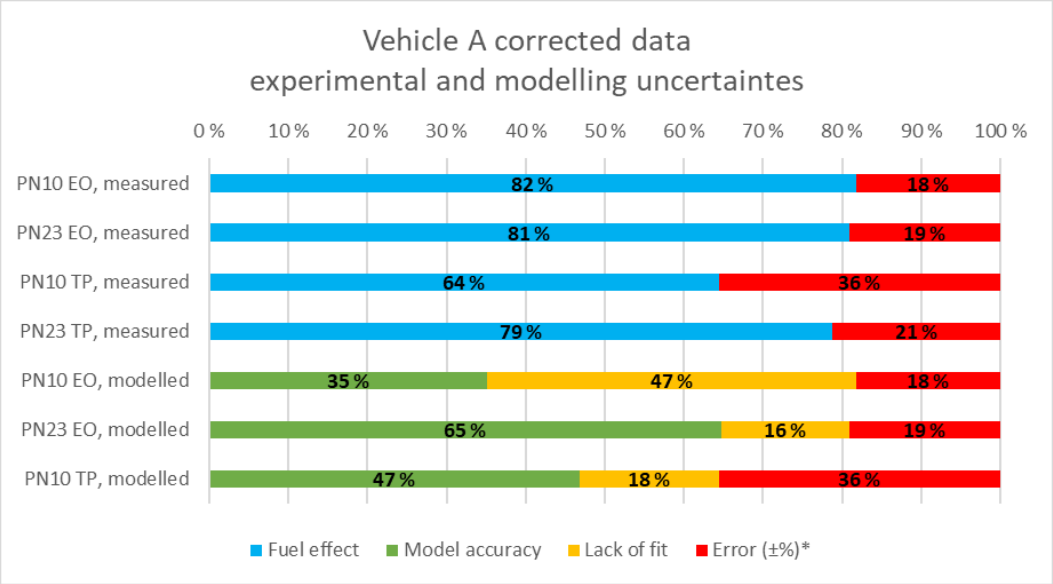


Figure 17.3 Calculated experimental and modelling uncertainties for Vehicle A (corrected)

Table ***17.10*** describes the influence of the individual variables on the model response for given fuel properties. Both PN_{10} EO and TP models included only one parameter, hence the magnitude of effect was determined as 100 %. For the PN_{23} EO, the increase per unit in aromatics was ca. double than for E70 but due to the higher range for E70, the magnitude of effect was slightly greater for E70 than for aromatics.

Table 17.10 The effect of the individual variables for the Vehicle A (corrected) models on PN-emissions.

Emission	Variable	Range low (%)	Range high (%)	Range (%)	Increase per unit (#*10^11/km]	Magnitude of effect (%)
PN 10 EO	IBP	27.0	40.0	13.0	-1.529	-100 %
PN23 EO	E70	13.2	52.1	38.9	0.033	56 %
	Aromatics	20.5	35.0	14.5	0.078	49 %
PN10 TP	IBP	27.0	40.0	13.0	0.002	100 %
PN23 TP						

17.3.2. Vehicle B

The final equations for vehicle B (uncorrected) used for the models were:

PN10 EO = C + a * x1 = 91.958 - 0.92608 * 10% vol
with an error obtained from the experimental data of ± 19 %

PN23 EO = C + a *x1 + b * x2 = -3.5072 + 0.7349 * C9 and >C9 Aromatics + 0.48249 * Aromatics
with an error obtained from the experimental data of ± 22 %

PN10 TP = C + a *x1 + b * x2 = -0.16278 + 0.020756 * Aromatics + 0.011117 * E70
with an error obtained from the experimental data of ± 11 %

PN23 TP = C + a *x1 + b * x2 = -0.1651 + 0.01822 * Aromatics + 0.012072 * E70

with an error obtained from the experimental data of ± 11 %

Table ***17.11*** describes the influence of the individual variables on the model response for given fuel properties. Highest significance for the model based on vehicle B uncorrected values was found for PN TP emissions. The TP emissions were in terms of error most stable, and the lack of fit remain overall very low for the corresponding models, as seen in Figure ***17.4***. Lowest model accuracy was determined for PN_{10} EO as no trend correction was applied. This was considered to result in a significant contribution to lack of fit.

Table 17.11 A summary describing the variables in their influence used for Vehicle B (with uncorrected values)

Vehicle B model summary, variables and their significance															
PN10 EO				PN23 EO				PN10 TP				PN23 TP			
Variables	Constant	P-value	Significance	Variables	Constant	P-value	Significance	Variables	Constant	P-value	Significance	Variables	Constant	P-value	Significance
Intercept	91.958	0.0012	**	Intercept	-3.5072	0.428	o	Intercept	-0.1628	0.1848	o	Intercept	-0.1628	0.185	o
per_vol_10	-0.926	0.0407	*	C9_and_C9_plus	0.7349	0.048	*	Aromatics	0.0208	0.0015	**	Aromatics	0.0208	0.002	**
				<C9_aromatics	0.4825	0.047	*	E70	0.0111	0.0003	***	E70	0.0111	0.000	***
Total		0.0407	*	Total		0.013	*	Total		0.000031	***	Total		0.00003	***

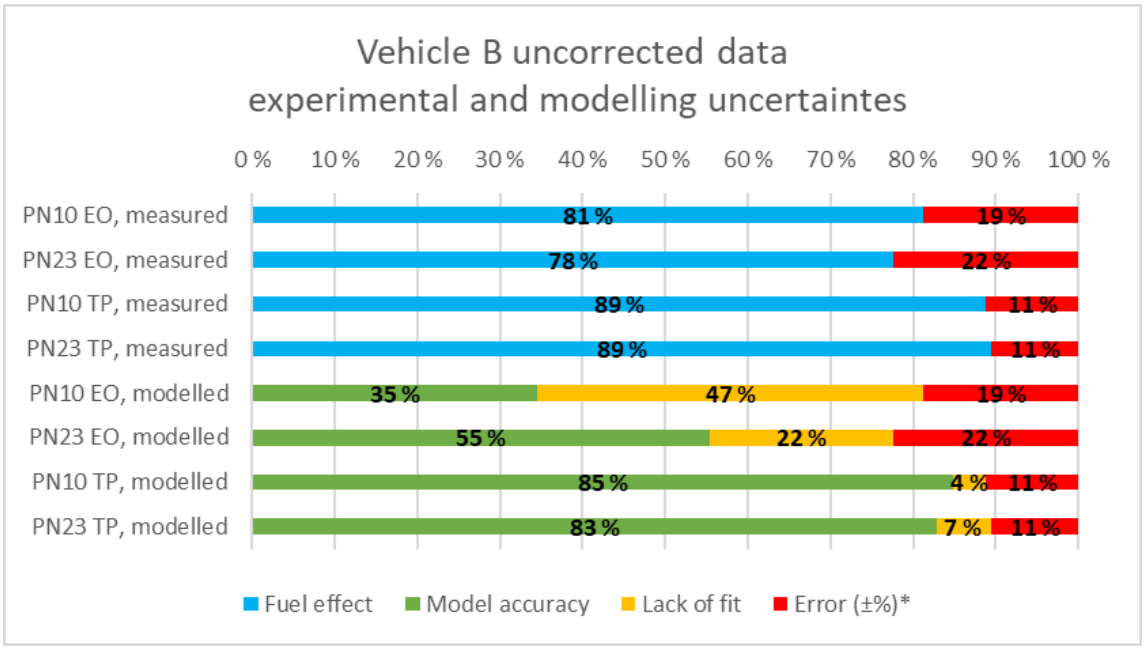


Figure 17.4 Calculated experimental and modelling uncertainties for Vehicle B (uncorrected)

Table ***17.12*** describes the influence of the individual variables on the model response for given fuel properties. All variables used in the models but one (10% vol for PN_{10} EO) contributed to an increase in PN emissions. The magnitude of effect varied depending on variable range between 42 to 62 %. For PN_{23} EO the model results were only affected by aromatics (<C9 aromatics and ≥C9 aromatics). The modelling results for PN_{10} TP and PN_{23} TP were both affected by aromatics and E70.

Table 17.12 The effect of the individual variables for the Vehicle B (uncorrected) models on PN-emissions.

Emission	Variable	Range low (%)	Range high (%)	Range (%)	Increase per unit (#*10^11/km]	Magnitude of effect (%)
PN 10 EO	per_vol_10	44.5	66.6	22.1	-0.9261	-100 %
PN23 EO	C9_and_C9_plus	5.5	12.5	7.0	0.7349	62 %
	<C9_aromatics	14.7	25.1	10.4	0.4825	60 %
PN10 TP	Aromatics	20.5	35.0	14.5	0.0208	43 %
	E70	13.2	52.1	38.9	0.0111	62 %
PN23 TP	Aromatics	20.5	35.0	14.5	0.0208	42 %
	E70	13.2	52.1	38.9	0.0111	61 %

The final equations for vehicle B (corrected) used for the models were:

PN10 EO = C + a *x1 + b * x2 = 23.227 + 0.7788 * Aromatics -0.37451 * ETBE
with an error obtained from the experimental data of ± 24 %

PN23 EO = C + a *x1 = -2.3813 + 0.52912 * Aromatics
with an error obtained from the experimental data of ± 23 %

PN10 TP = C + a *x1 + b * x2 = -0.16288 + 0.020656 * Aromatics + 0.011323 * E70
with an error obtained from the experimental data of ± 10 %

PN23 TP = C + a *x1 + b * x2 = -0.15142 + 0.017534 * Aromatics + 0.012216 * E70
with an error obtained from the experimental data of ± 10 %

Table ***17.13*** describes the influence of the individual variables on the model response for given fuel properties. Similarly, to the uncorrected vehicle B models, the highest model accuracy was reached for both PN TP emissions. The corrections made for the PN trends evidently improved the R^2 for PN EO models with a slight penalty in accuracy for the PN TP results. However, the penalty obtained for PN TP was still considered relatively low, thus it was generally seen that the usage of the corrected input data was improving the quality of the modelling.

Table 17.13 A summary describing the variables in their influence used for Vehicle B (with corrected values)

Vehicle B model summary, variables and their significance																
PN10 EO				**PN23 EO**				**PN10 TP**				**PN23 TP**			
Variables	**Constant**	**P-value**	**Significance**	**Variables**	**Constant**	**P-value**	**Significance**	**Variables**	**Constant**	**P-value**	**Significance**	**Variables**	**Constant**	**P-value**	**Significance**
Intercept	23.2270	0.0138	*	**Intercept**	-2.3813	0.538	o	**Intercept**	-0.1629	0.2061	o	**Intercept**	-0.1514	0.301	o
Aromatics	0.7788	0.0108	*	**Aromatics**	0.5291	0.003	**	**Aromatics**	0.0207	0.0021	**	**Aromatics**	0.0175	0.010	*
ETBE	-0.3745	0.05	*					**E70**	0.0113	0.0003	***	**E70**	0.0122	0.001	***
Total		0.0056	**	**Total**		0.003	**	**Total**		0.000041	***	**Total**		0.00012	***

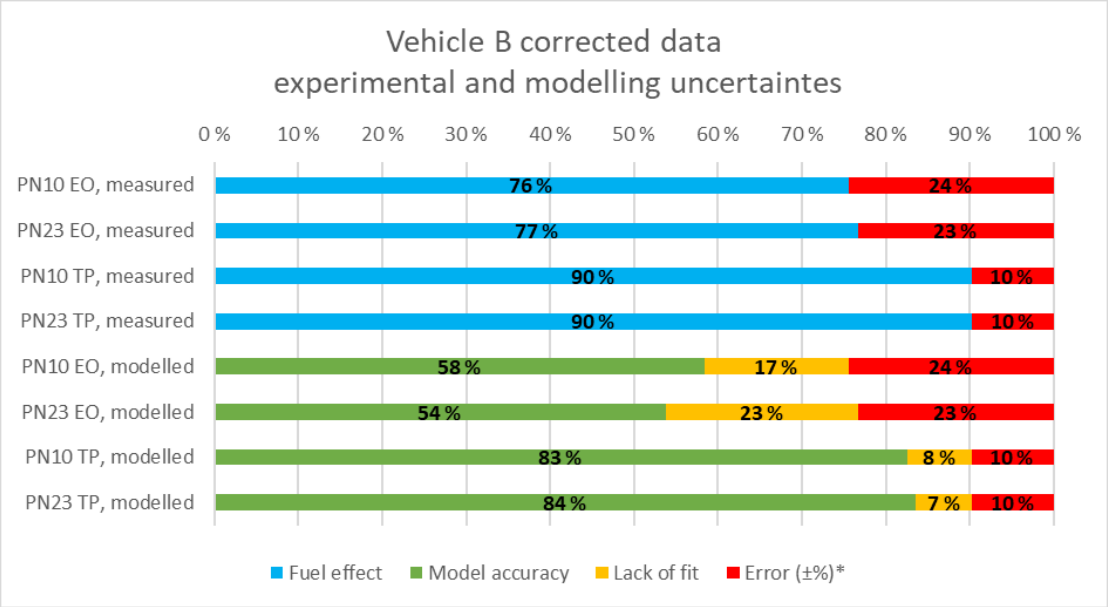


Figure 17.5 Calculated experimental and modelling uncertainties for Vehicle B (corrected)

Table 17.14 describes the influence of the individual variables on the model response for given fuel properties. All variables used in the models but one (10% vol for PN10 EO) contributed to an increase in PN emissions. The magnitude of effect varied depending on variable range between -42 to 62 %.

For PN23 EO the model results were solely affected by fuel total aromatics. PN10 TP and PN23 TP the model results were most significantly affected by an increase in E70 and fuel aromatics.

Table 17.14 The effect of the individual variables for the Vehicle B (corrected) models on PN-emissions.

Emission	Variable	Range low (%)	Range high (%)	Range (%)	Increase per unit (#*10^11/km]	Magnitude of effect (%)
PN 10 EO	Aromatics	20.5	35.0	14.5	0.7788	67 %
	ETBE	0.0	18.8	18.8	-0.3745	-42 %
PN23 EO	Aromatics	20.5	35.0	14.5	0.5291	100 %
PN10 TP	Aromatics	20.5	35.0	14.5	0.0207	42 %
	E70	13.2	52.1	38.9	0.0113	62 %
PN23 TP	Aromatics	20.5	35.0	14.5	0.0175	36 %
	E70	13.2	52.1	38.9	0.0122	67 %

17.3.3. Vehicle C

The final equations for vehicle C (corrected) used for the models were:

PN10 EO = C + a * x1 + b * x2 + c * x3 + d * (x1 * x3) = -66.839 + 0.064671 * 20% vol + 0.22542 * 95% vol + 6.0519 * C9 and >C9 Aromatics – 0.087005 * (20% vol + 95% vol)with an error obtained from the experimental data of ± 14 %

PN23 EO = C + a * x1 = 0.36143 + 0.42513 * C9 and >C9 Aromatics with an error obtained from the experimental data of ± 27 %

PN10 TP = C + a *x1 + b * x2 = 0.0097716 + 0.0012325 * 30 vol%with an error obtained from the experimental data of ± 9 %

PN23 TP = C + a *x1 + b * x2 = 0.084866 - 0.00099683 * <C9 aromaticswith an error obtained from the experimental data of ± 4 %

Table 17.15 describes the influence of the individual variables on the model response for given fuel properties. The model created contained only one parameter for the models created for PN_{23} EO, PN_{10} TP and for PN_{23} TP. Furthermore, the significance for these estimates remains relatively low. However, as the process of stepwise elimination for PN_{10} EO introduced a new, non-linear variable, the model seemed to result in a reasonably high significance without any penalties in the coefficient of determination. The experimental data shows that due to the nature of the PFI engine, the PN EO formation was most dominant for sub 23 nm particulates, and thus enabling a more detailed modelling for PN_{10} EO compared to other PN emissions. The high accuracy together with low lack of fit for PN_{10} EO model seen in ***Figure 17.6*** initially suggests that the fuel effect could supposedly be predicted with high precision and low modelling error for fuel data with given specifications. This was not the case for e.g., PN_{23} EO as the model accuracy was determined as only around 0.32. Despite the relatively low contribution of noise for the PN TP emissions, the corresponding models suffered from a relatively significant lack of fit. The results obtained both experimentally and by modelling suggests that the impact of fuel characteristics remain lower for PFI applications compared to vehicles equipped with GDI systems. The TP PN emissions were therefore seen more random rather than dependent of fuel properties.

Table 17.15 A summary describing the variables in their influence used for Vehicle C (with corrected values)

Vehicle C model summary, variables and their significance															
PN10 EO				PN23 EO				PN10 TP				PN23 TP			
Variables	Constant	P-value	Significance	Variables	Constant	P-value	Significance	Variables	Constant	P-value	Significance	Variables	Constant	P-value	Significance
Intercept	-66.8	0.0192	*	Intercept	0.3614	0.805	o	Intercept	0.0098	0.0009	***	Intercept	0.0849	0.001	***
per_vol_20	0.6467	0.0739	o	C9_and_C9_plus	0.4251	0.017	*	per_vol_30	0.0012	0.0394	*	C9_aromatic	-0.0010	0.039	*
per_vol_95	0.2225	0.0144	*												
C9 and C9+ aro (% v/v)	6.0519	0.0173	*												
20% vol * C9 and C9+ aro	-0.0870	0.0285	*												
Total		0.0025	**	Total		0.017	*	Total		0.03	*	Total		0.0343	*

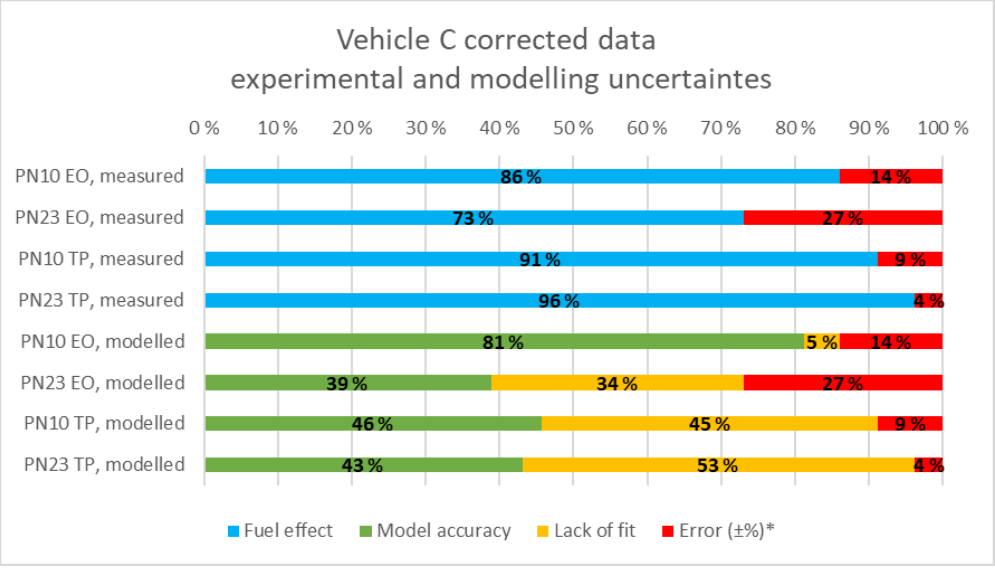


Figure 17.6 Calculated experimental and modelling uncertainties for Vehicle C (corrected)

Because MATLAB introduced a non-linear factor to the PN_{10} EO model equation (e * x1 * x3), the magnitude of effect may not be equally compared with the other variables as shown in ***Table 17.16***. The non-linear equation does not correspond to the magnitude of effect similarly to any linear equation as the variables with more dependencies will influence the outcome with more than only one output.

Table 17.16 The effect of the individual variables for the Vehicle C (corrected) models on PN-emissions.

Emission	Variable	Range low	Range high	Range	Increase per unit (#*10^11/km]	Magnitude of effect (%)
PN 10 EO	per_vol_20	43.9	76.4	32.5	0.647	130 %
	per_vol_95	153.7	178.2	24.5	0.223	34 %
	C9 and C9+ aro (% v/v)	5.5	12.5	7.0	6.052	263 %
	20% vol * C9 and C9+ aro	-67.0	-28.9	38.2	-0.087	-21 %
PN23 EO	C9_and_C9_plus	5.5	12.5	7.0	0.425	100 %
PN10 TP	per_vol_30	58.4	84.9	26.5	0.001	100 %
PN23 TP	<C9_aromatics	14.7	25.1	10.4	-0.001	-100 %

17.4. ASSESSMENT OF CREATED MODELS AND MODELLING VALIDATION

Each final model was individually validated by comparing the model results with the experimentally produced PN emissions. The robustness of each model was further assessed with two cases where two fuels were removed from the model data input. For all cases, the randomly removed fuels for the first case were fuels 3 and 6 and for the second case fuel 9 and 10. Fuel 3 and 6 were purely randomly selected meanwhile fuels 9 and 10 were removed because they were formulated fuels from the previous study (Gasoline particulate study phase 1). For the validation process, the error margins were defined based on the deviation defined in the experimental part as “noise” or pure error.

17.4.1. Vehicle A

The validation of Vehicle A PN_{10} EO is shown in ***Figure 17.7***. Due to the relatively low coefficient of determination (R^2 = 0.35) obtained for the model, the slope between the data trend and bisector was rather poor. Additionally, the data indicates that the spread was found reasonably high. Nevertheless, all modelled data points were still within the acceptable error margins. The issue related to lack of fit is seen clearly as the slope of the trendline is relatively far from 1, and the model seems to underestimate PN_{10} EO emissions for fuels resulting in higher PN_{10} EO emissions and vice versa. Despite the data being within the acceptable margins, any estimation outside the given fuel properties may likely over or underestimate the PN_{10} EO emissions.

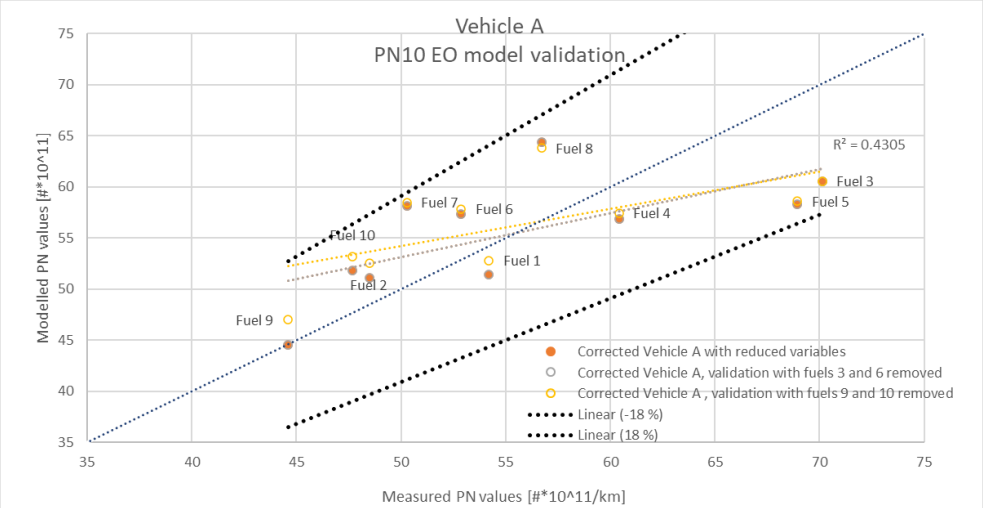


Figure 17.7 Model validation for vehicle A corrected PN_{10} EO

The modelled results for PN23 EO emissions were found more in line with the experimentally produced data. ***Figure 17.8*** shows that the trendline corresponds relatively well with the experimental data and the model response in fuel removal is generally minor. All produced data was found within the given error margins of experimental noise.

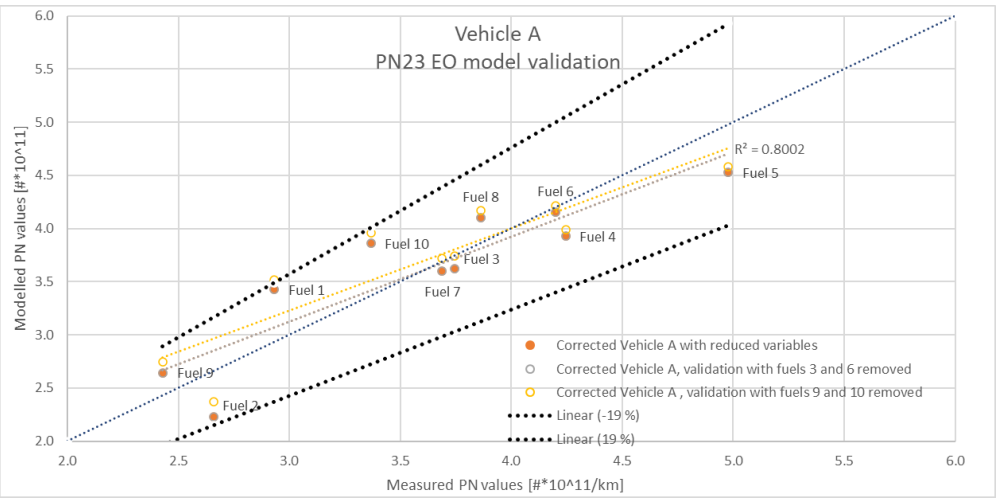


Figure 17.8 Model validation for vehicle A corrected PN_{23} EO

The validation results for PN_{10} TP model are shown in ***Figure 17.9***. The PN_{10} TP model suffered from some inaccuracy due to the extremely low PN_{10} emissions caused by the vehicles effective GPF. As a result, the experimentally obtained absolute fuel effect remain low (in the range of max 3x10^9 #/km). The low PN TP emissions are a challenge for the modelling as the change in PN emissions are typically minor. This turn is in favour for contribution of modelling error and reduce the accuracy for distinguishing any fuel effect.

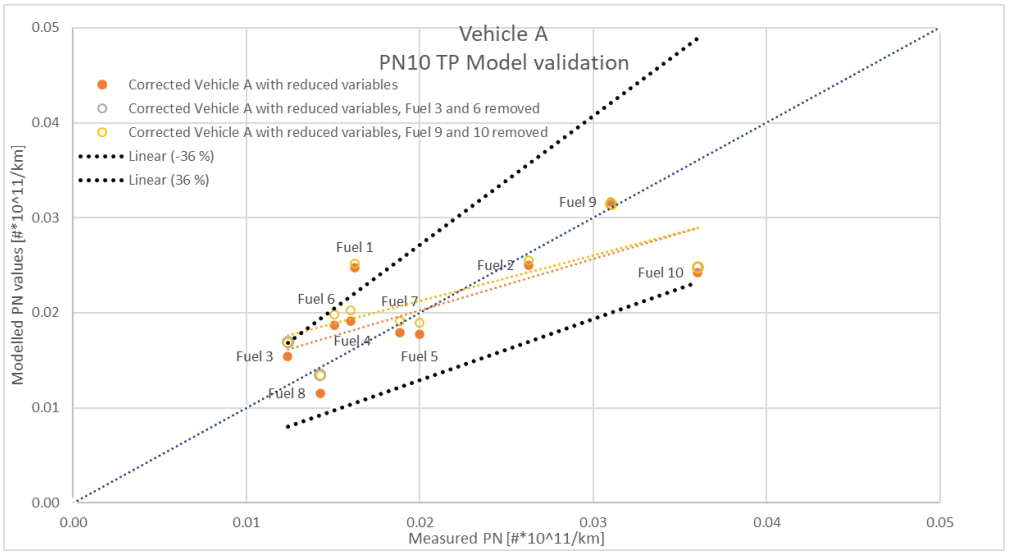


Figure 17.9 Model validation for vehicle A corrected PN_{10} TP

17.4.2. Vehicle B

The primary advantage obtained from a successful trend correction is well demonstrated by comparing the two PN_{10} EO models created for vehicle B. The model created by using the uncorrected data has a significant bias in the correlation (and thus different constant for slopes) between trendline and bisector as shown in ***Figure 17.10***. By implementing the trend corrected data sets, the slope changes in favour of improving the correlation between modelled and experimental data (***Figure 17.11***). The model implementing corrected data seems additionally more accurate as the data set fits well within the given error margins. By comparing the trend fit of corresponding PN_{10} EO models in respect to experimental data shown in ***Figure 17.12*** concludes that the PN_{10} EO model with corrected values is more in line with the experimental data.

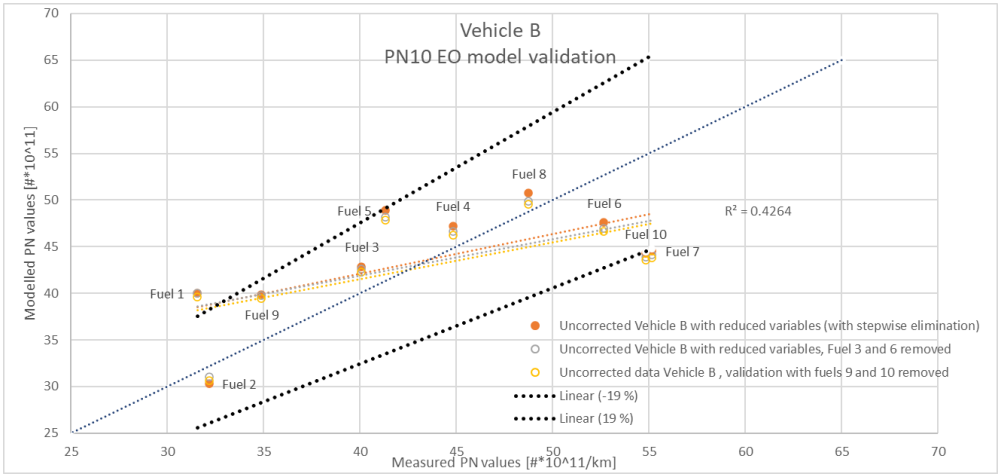


Figure 17.10 Model validation for vehicle B (uncorrected) PN_{10} EO

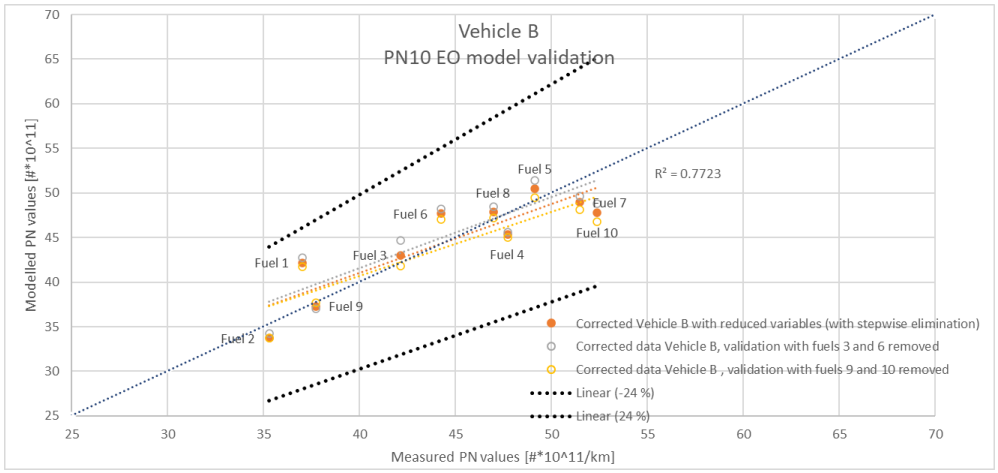


Figure 17.11 Model validation for vehicle B (corrected) PN_{10} EO

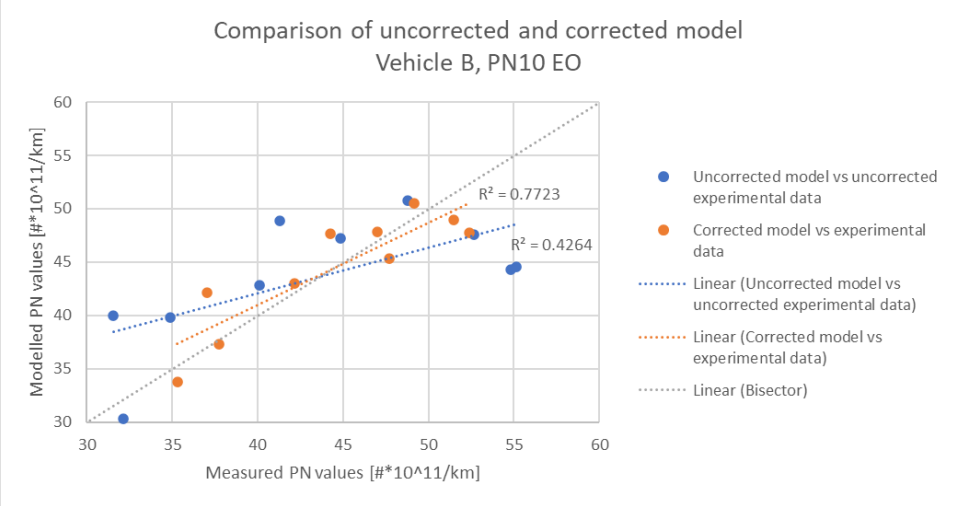


Figure 17.12 Comparison of fit between measured and modelled data for uncorrected and corrected data input

Due to the nature of the trends obtained (and less correction required) in the experimental work, the influence of correction was not as great for PN_{23} EO data. However, the output of the model based on the corrected data is evidently more robust compared to the uncorrected model as the error caused by the model output with fuels removed cause less deviation in the output data.

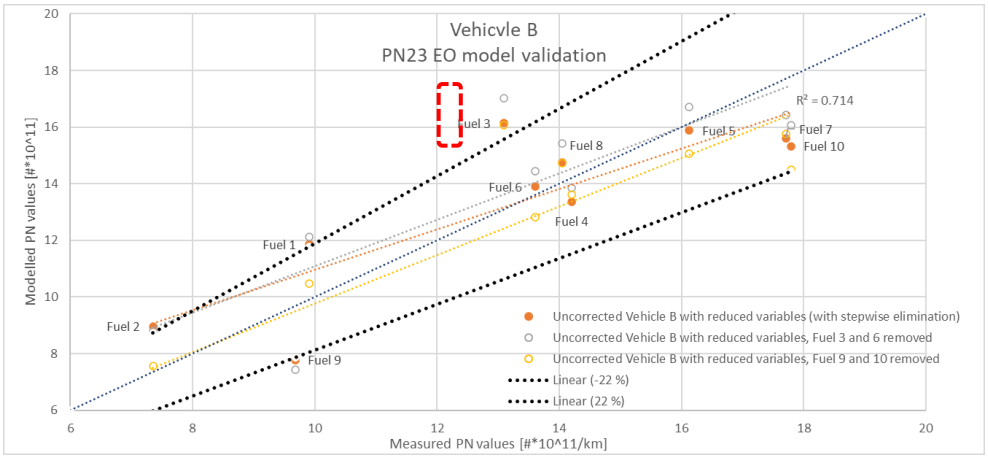


Figure 17.13 Model validation for vehicle B (uncorrected) PN_{23} EO

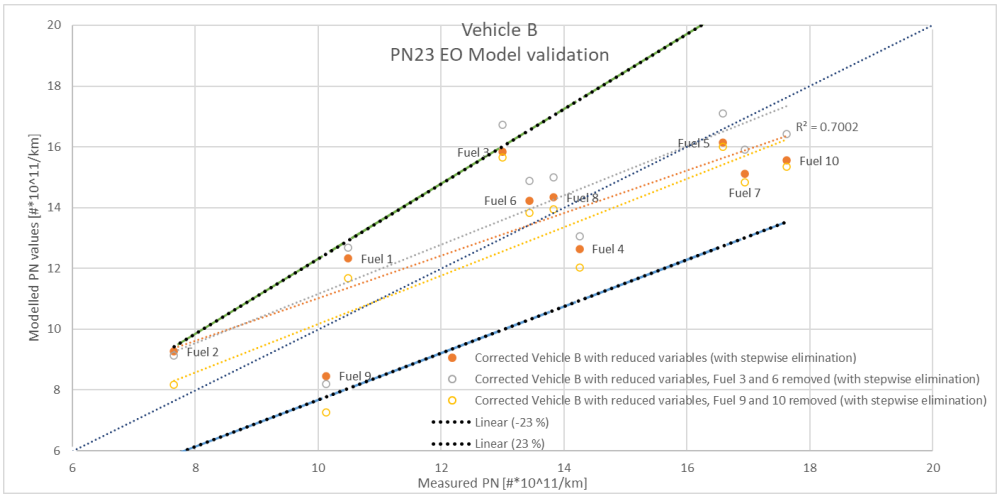


Figure 17.14 Model validation for vehicle B (corrected) PN_{23} EO

For vehicle B, the deviation of the experimental TP emissions was found overall lower compared to EO results. The average deviation, i.e., pure error was defined as ca. 10 – 11 % (compared to ca. 19 % - 24 % for the EO data). As the data was more robust and data trends were less aggressive, the trend corrections for the PN TP emissions were less significant. The fit for both, uncorrected and corrected PN_{10} TP models were considered good, and the data spread was concluded to be well within the tolerated error margins even with fuel inputs removed.

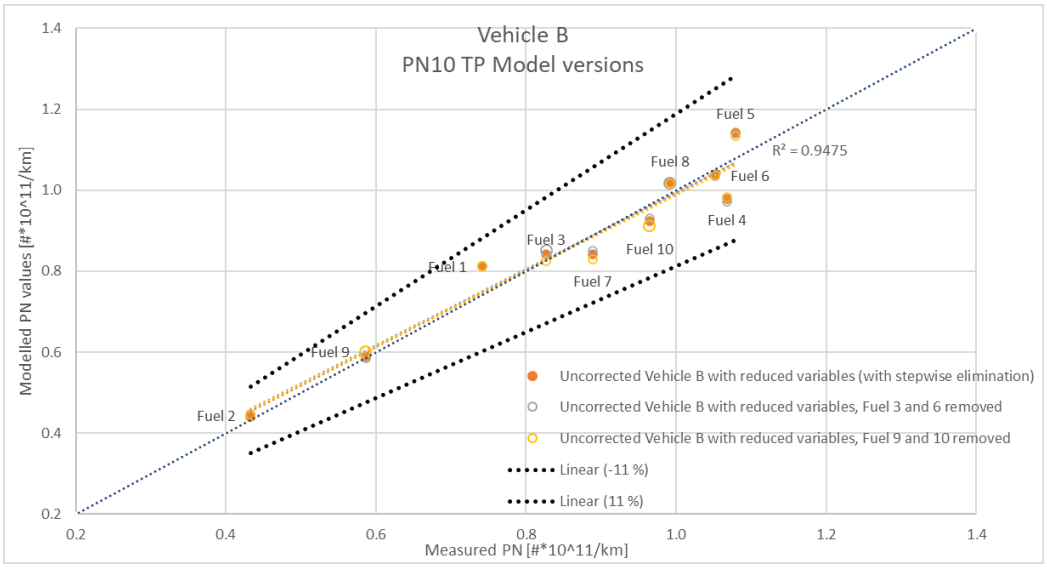


Figure 17.15 Model validation for vehicle B (uncorrected) PN_{10} TP

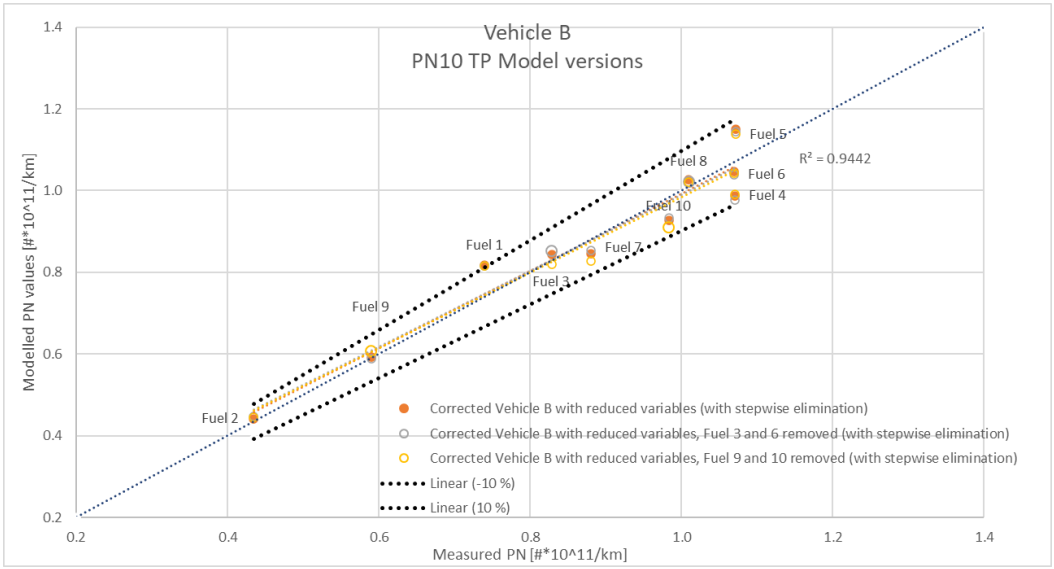


Figure 17.16 Model validation for vehicle B (corrected) PN_{10} TP

The model validation conducted for vehicle B PN_{23} TP shown in ***Figure 17.17*** and in ***Figure 17.18*** indicates that the fuel response of both models was highly similar. The correlation between the two models was found close to 1 as seen from ***Figure 17.19***. However, as the data correction of the experimental data reduced the deviation and thus the average error by ca. 1 % (abs), some of the data fell outside the defined error margins.

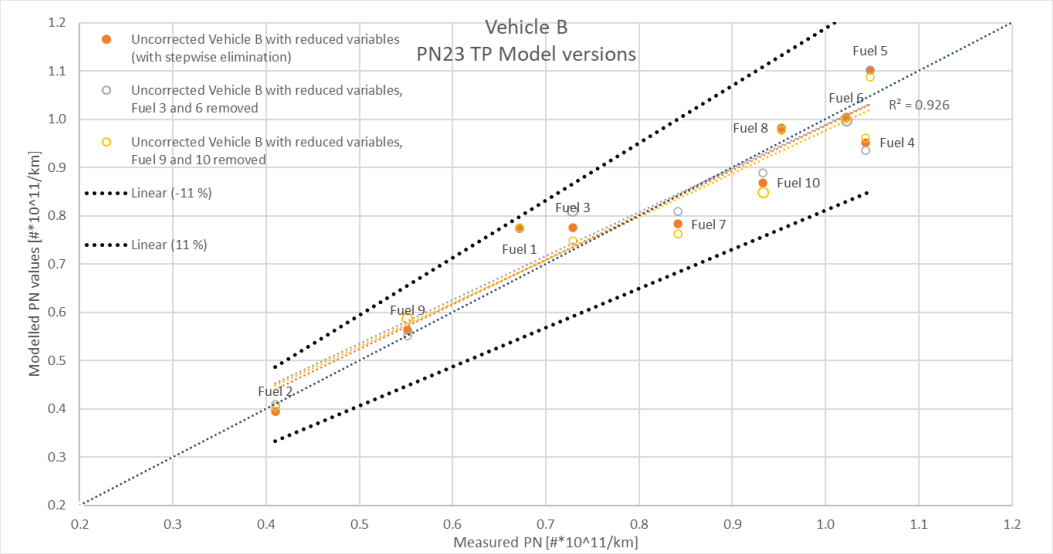


Figure 17.17 Model validation for vehicle B (uncorrected) PN_{23} TP

Figure 17.18 Model validation for vehicle B (corrected) PN_{23} TP

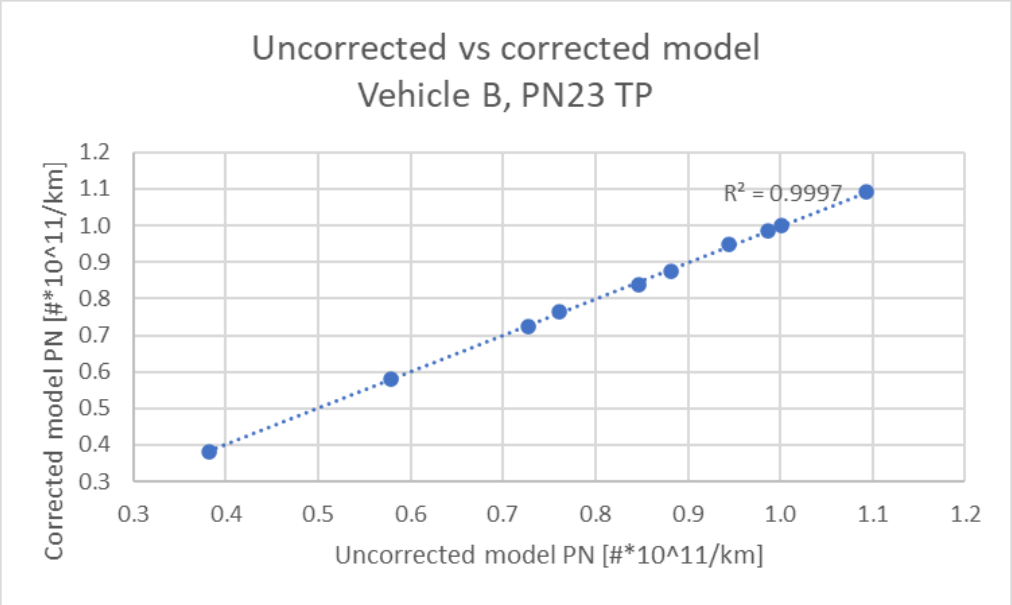


Figure 17.19 Comparison of PN23 TP uncorrected vs corrected model output

17.4.3. Vehicle C

Because the quantity of fuel properties with reasonable correlation with the vehicle C PN emissions was poor correlation between the initial experimental data and the given fuel properties were typically low, ca. 0.6 – 0.7; therefore, relatively large error from vehicle C models was expected. The validation results of the model created for PN_{10} EO was found somewhat contradictory, shown in ***Figure 17.20***. The initial impressions were that the model was very accurate and thus the fit of the model was excellent. However, the model was found sensitive to any changes in the input data (i.e. fuel removal), resulting in some deviation in the results for those fuels which were removed for creating the model equation. It's likely that the model is very sensitive to any general change in fuel properties and not predictive.

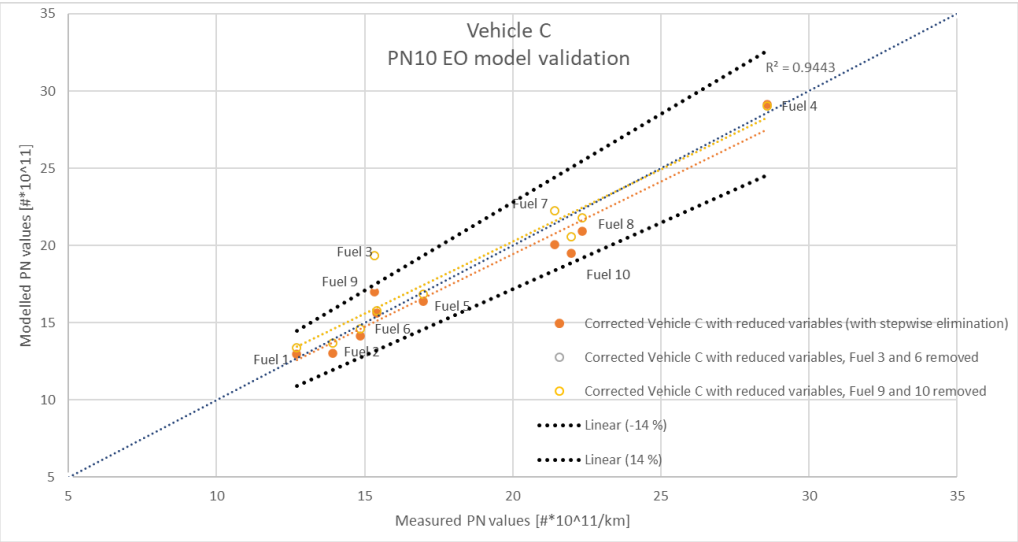


Figure 17.20 Model validation for vehicle C (corrected) PN_{10} EO

Because the correlation between fuel properties and PN emissions for vehicle C was found overall low, the developed models were found to suffer from two main issues:

1. Generally, the fitting of trendlines were found poor for PN23 EO, PN10 TP and PN23 TP emissions, shown in Figure ***17.21***, Figure ***17.22*** and Figure 17.23
2. The data spread and overall deviation was significant even for fuels that were not removed during the validation process.

The validation of vehicle C models shows that it is highly questionable if any accurate models could be created whatsoever. This problem was identified already during the experimental research, as the correlations between the fuel properties and PN emissions were generally found poor. The accuracy of the models for PN_{23} EO, PN_{10} TP and PN_{23} TP could potentially be improved by adding input variables, but this would evidently decrease the robustness of the models, as shown for the PN_{10} EO model. The overall conclusion based on the findings is that any PN modelling for engines equipped with PFI engines is most likely challenging.

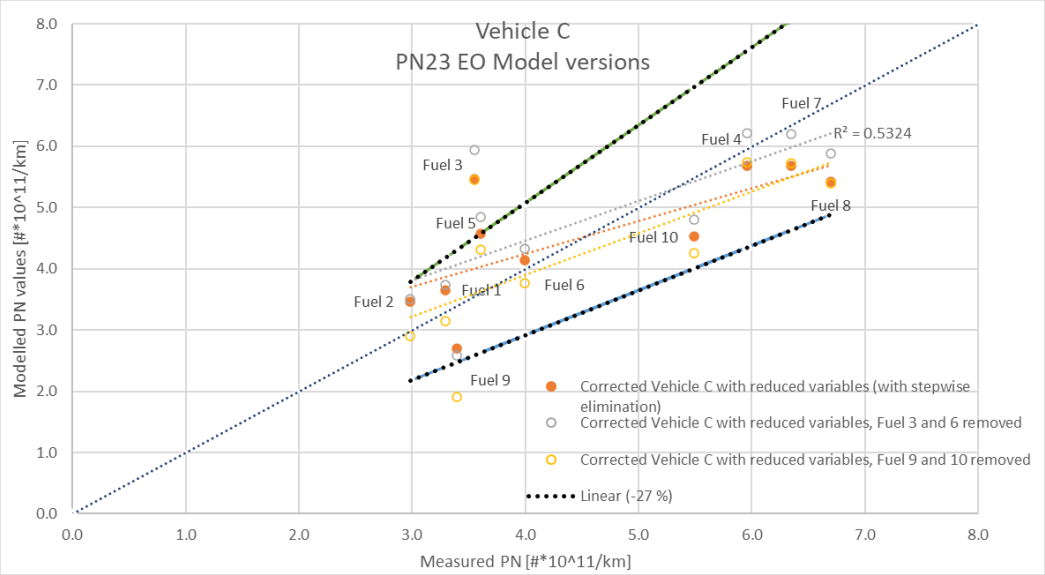


Figure 17.21 Model validation for vehicle C (corrected) PN_{23} EO

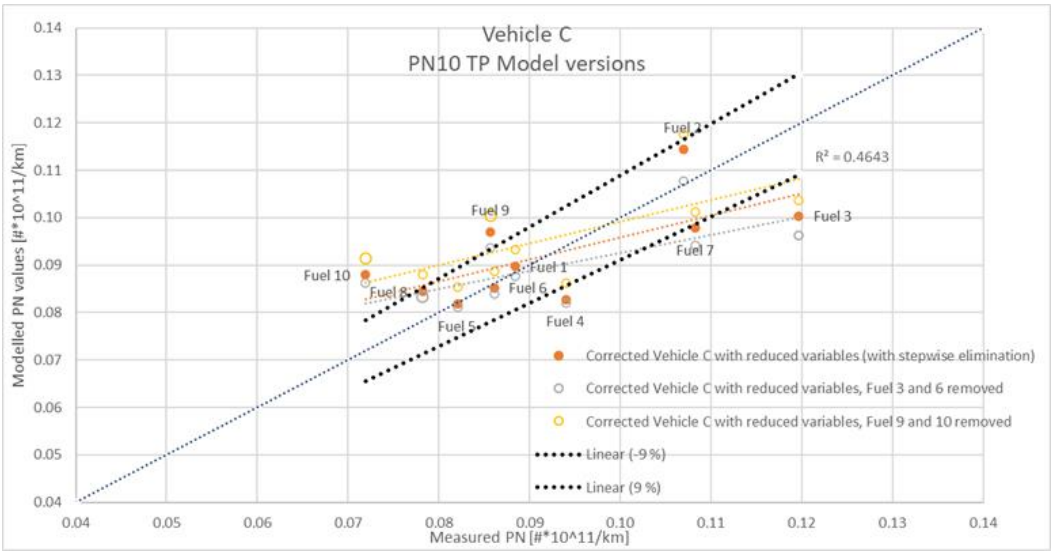


Figure 17.22 Model validation for vehicle C (corrected) PN_{10} TP

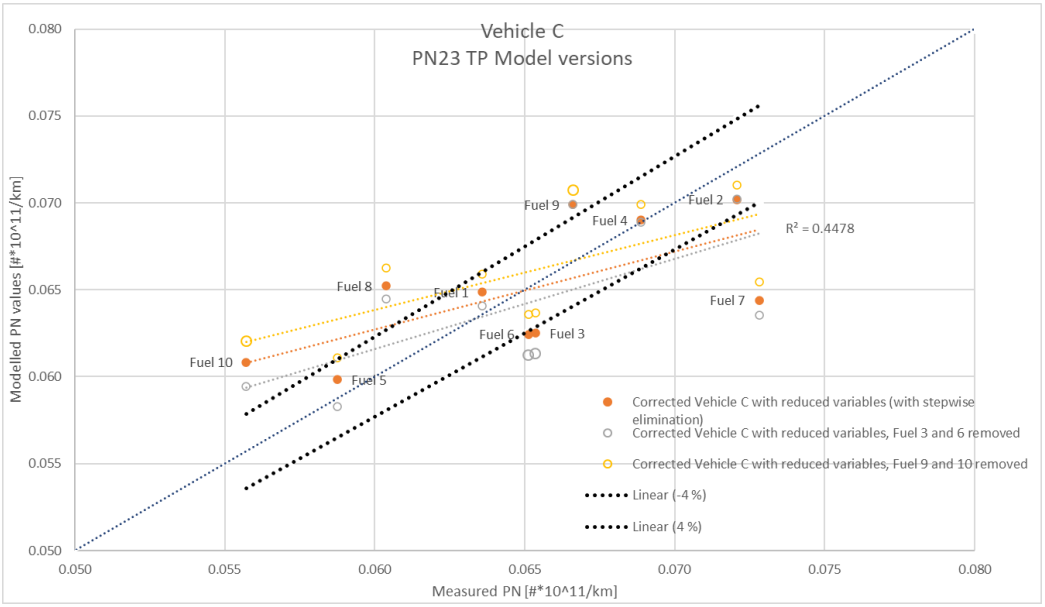


Figure 17.23 Model validation for vehicle C (corrected) PN_{23} TP

17.4.4. A comparison of vehicle specific modelling results

As the order of magnitude for PN emissions varied significantly between each test vehicle, only the relative effects between each model are comparable. The relative comparison was performed by calculating the relative change of PN emissions in relation to the output of one fixed fuel, e.g. in this case, Fuel 1. The comparison of the relative effect on PN_{10} EO models are presented in ***Figure 17.24***, for PN_{23} EO in ***Figure 17.25***, for PN_{10} TP in ***Figure 17.26*** and for PN_{23} TP in ***Figure 17.27***.

The comparison between the relative modelling results indicates that the models created for each vehicle are relatively vehicle specific. However, PN EO emission for the vehicles with GDI engines are generally more similar compared to the model results of the PFI vehicle. For example, the relative change for the modelled PN_{10}

EO emissions are evidently higher for vehicle C for certain fuels, such as for fuels 4, fuel 7, fuel 8, fuel 9 and fuel 10 (***Figure 17.24***). A similar, albeit a not as strong effect may be seen for PN_{23} EO results (***Figure 17.25***). The effect for PN TP emissions was found more "random" due to the influence of GPF. Generally, the characteristics of the GPF seem to influence the PN emissions for each vehicle differently.

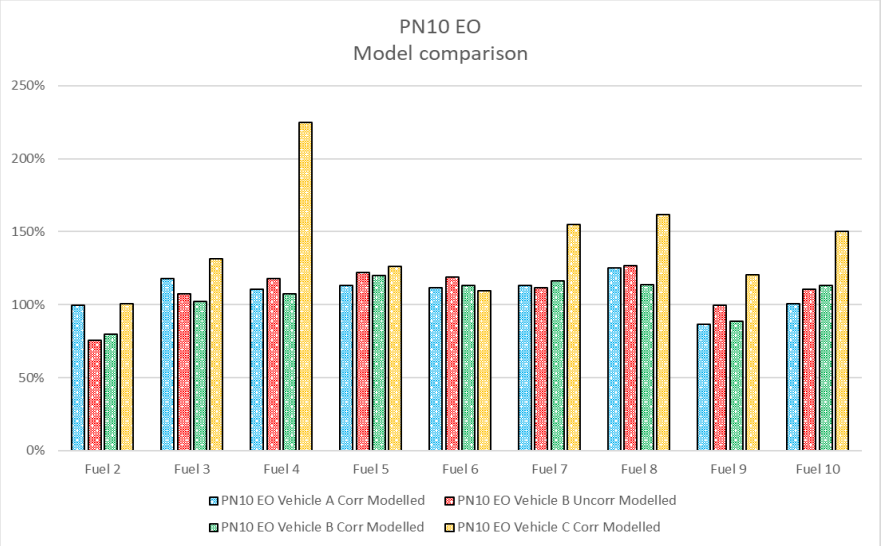


Figure 17.24 Modelling results of PN_{10} EO relative to fuel 1. All created final models included.

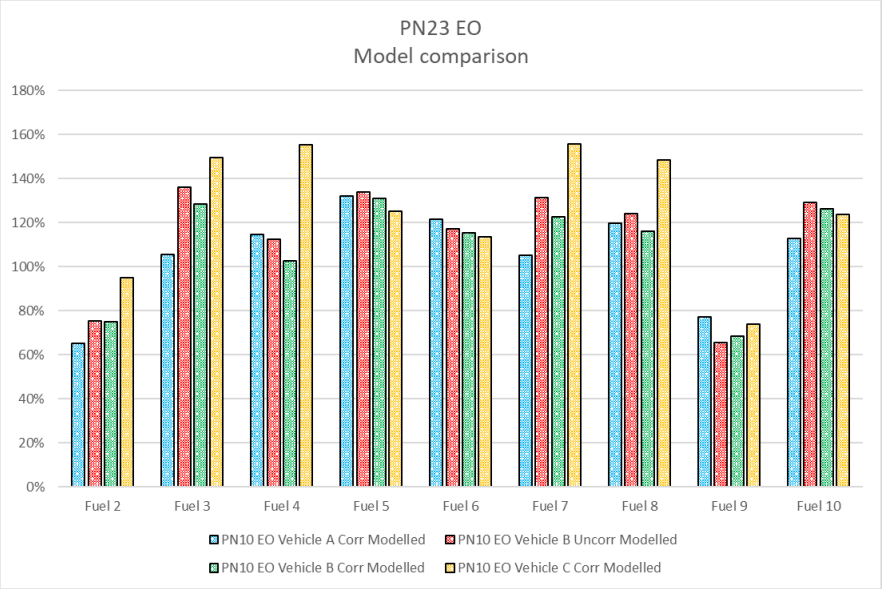


Figure 17.25 Modelling results of PN_{23} EO relative to fuel 1. All created final models included.

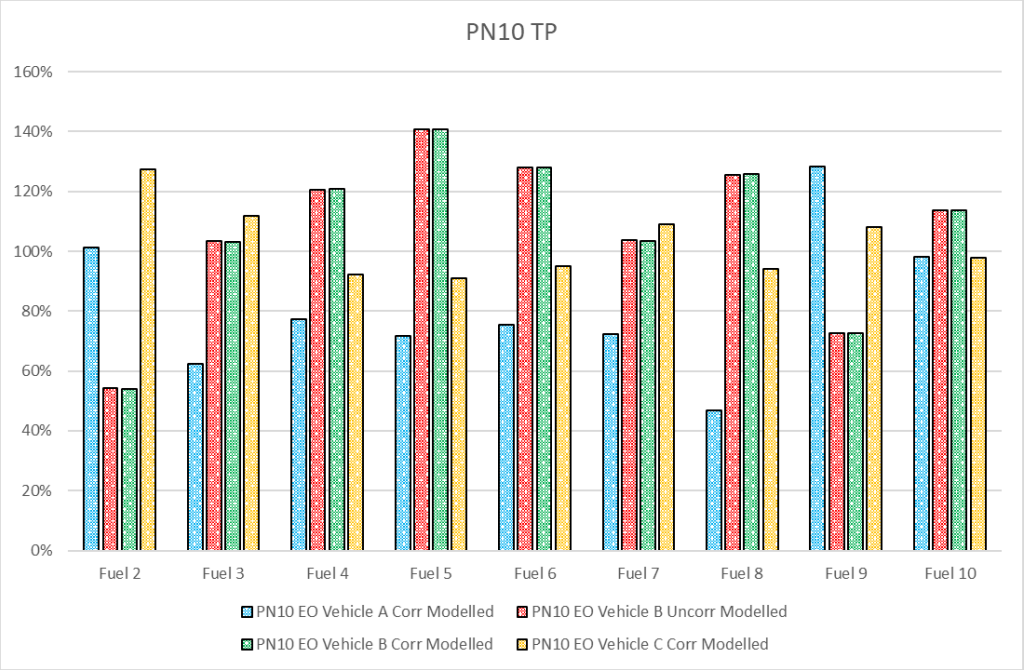


Figure 17.26 Modelling results of PN_{10} TP relative to fuel 1. All created final models included.

Figure 17.27 Modelling results of PN_{23} TP relative to fuel 1. All created final models included.

17.4.5. A comparison of the models with results from Phase 1

The model output created in this study was compared and validated against the results produced in the particulate emission study phase 1. Because the models

created for Vehicle B was found most robust, its results were seen most naturally to be compared with corresponding modelling obtained from phase 1. The fuel specific PN_{23} TP results were calculated using the equations created in phase 1.

Figure 17.28 shows the absolute PN_{23} TP results for vehicle B obtained with Phase 1 model equations together with corresponding measured and modelled (corrected) PN emissions. The phase 1 results are evidently overpredicting the PN emissions in terms of absolute values on average by a factor between 4.32 to 4.59 for the WLTC cold start. The modelling output obtained from the hot start (E150 x Oxygenates Interaction Model, WLTC hot) is not shown in ***Figure 17.28*** because the model overpredicts the PN emissions with a factor of 10.78. A major contributor for the overprediction is most likely caused by the differences in test type. In phase 1, WLTP was used as test cycle to obtain the experimental data, meanwhile and RDE-simulating test cycle. These test cycles are not comparable by any aspects, as the time, distance and cycle profile do not correlate in any terms. Furthermore, the ambient temperature conducted in phase 1 was 23 °C, meanwhile for phase 2, 12 °C was used. Lastly, a great contributor for vehicle emissions are the simulated road loads. The road loads and overall emission performance for all vehicles tested in phase 2 were compared to the CoC values, and the emission response was found relatively good.

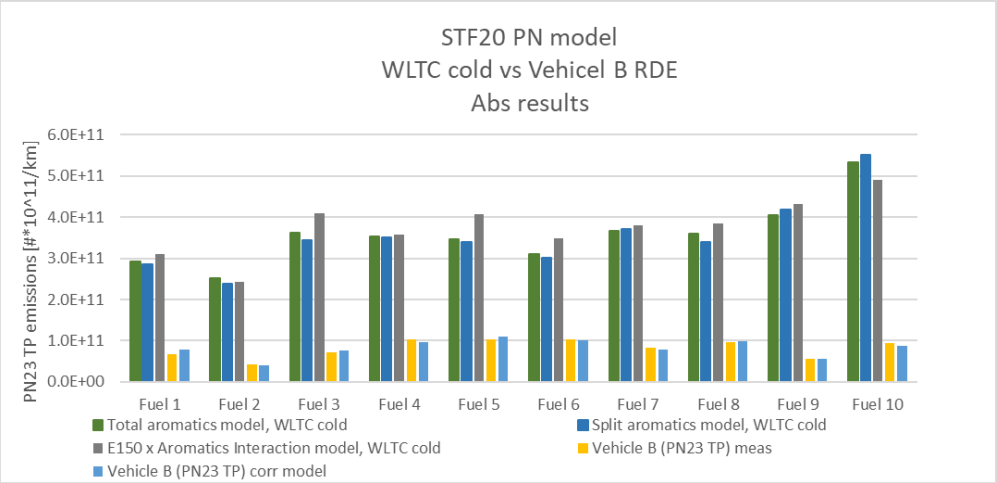


Figure 17.28 Comparison of PN23 EO emissions obtained from phase 1 models and Vehicle B corrected output

Due to the response differences in terms of absolute values, only relative results should be compared. The relative results from corresponding fuel modelling were calculated as a relative fuel change in respect to the average PN_{23} value calculated from all fuels. ***Figure 17.31*** illustrates the fuel response for each PN model. The relative changes in the output of the models created in phase 1 were typically not within the same magnitude with the measured, not modelled, PN results obtained in phase 2. Nevertheless, a similar trend was found for certain fuels: for fuels 1, 2 and 10, all models predicted the same direction in PN results. This was not the case for fuels 3 to 9, as the variation in fuel response was relatively random. However, the response of the model produced in phase 2 resulted typically closest to the measured values.

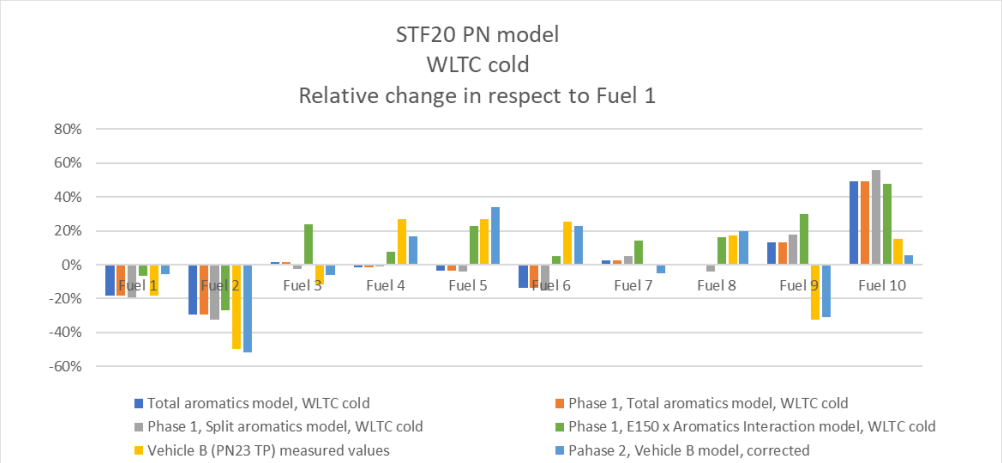


Figure 17.29 The relative change in PN23 TP emissions compared to fuel 1 with for models created in phase 1 and phase 2.

The same effect can be seen when comparing the correlation between the experimentally measured PN values with each model output (***Figure 17.30***). The correlation of the model created in phase 2 is well in line with the experimental data with an R^2 value of 0.9251. However, this was not the case for the models obtained from phase 1. The coefficient of determination varied between 0.08 and 0.018. These comparisons give evidence that models based on results obtained from different test conditions and tests cycles are not directly transferrable for generally predicting PN emission behavior.

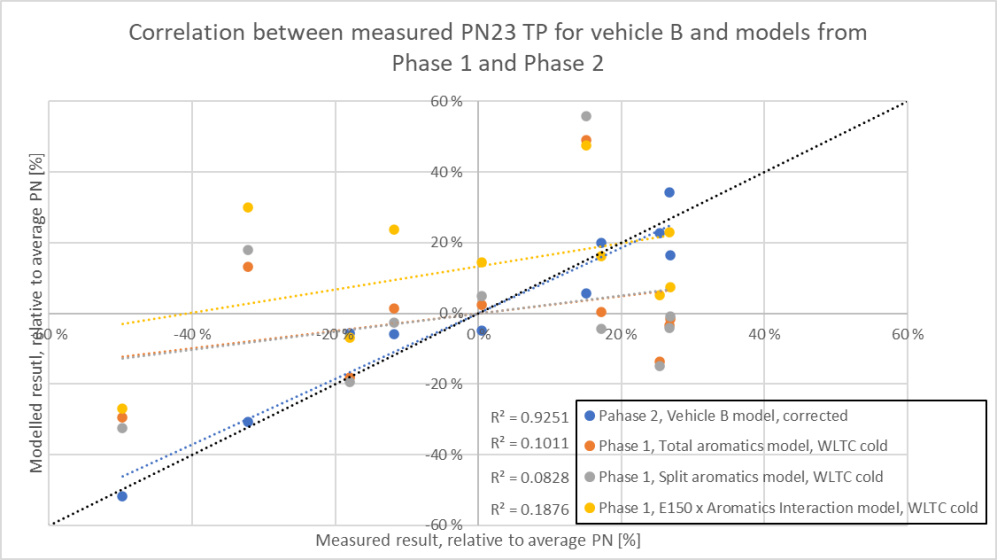


Figure 17.30 The correlation between absolute change for each model (phase 1 + phase 2) with experimentally obtained PN_{23} TP results

17.5. DEVELOPMENT OF A GENERAL MODEL

In order to assess the potential for using the created models with other vehicles (i.e. cross-modelling), the PN models of one GDI vehicle (vehicle B, corrected values) were further tested against experimental results obtained with the other

GDI vehicle, vehicle A. The justification behind using vehicle B model as a starting point was initially that the correlation between the fuel properties and PN results were found overall highest for this vehicle and the fit for the modelled results correlated reasonably well with the experimental data, especially for PN TP emissions. Secondly, as the models created for vehicle B using the corrected data improved the fit for the model trends, the model with corrected data was used. Another option would have been using vehicle A as a starting point, but as no reasonable model for vehicle A PN_{23} TP emissions had been identified, it was seen that the models created for vehicle A was missing data for further cross-modelling potential. No data obtained from the PFI was either used in this study as the central fuel parameters were found to be rather different than for the two other vehicles. Additionally, as seen above, the modelled fuel response obtained for PN emissions with vehicle C was typically least comparable with the two other vehicles, thus no further analysis was seen worthwhile to be performed for that vehicle in question.

The assessment of cross-modelling potential was conducted by using the absolute PN emissions for vehicle A using the experimental results acquired for fuel 1 as a reference. Then the relative model (relative fuel changes in respect to fuel 1) obtained for vehicle B was multiplied for each corresponding fuel in relation to vehicle A, fuel 1 input. As a result, an output PN number for each fuel was obtained for each emissions type, PN_{10} EO, PN_{23} EO, PN_{10} TP and PN_{23} TP.

Figure 17.31 illustrates the measured PN_{10} EO emissions for vehicle A, together with modelled vehicle A data and with the relative model created from vehicle B data. Interestingly, all results predicted with the relative model were within the error margins of the actual predictions obtained from the model created specifically for vehicle A, PN_{10} EO. This was however not the case when comparing the average values estimated from the relative model and the measured values, albeit the fuel response was estimated reasonably confidently for some of the fuel outputs. Based on the findings it may be concluded that the relative model may in some extent be used for predicting outlines of other vehicles PN behavior, but no absolutely accurate predictions using the relative model should be withdrawn.

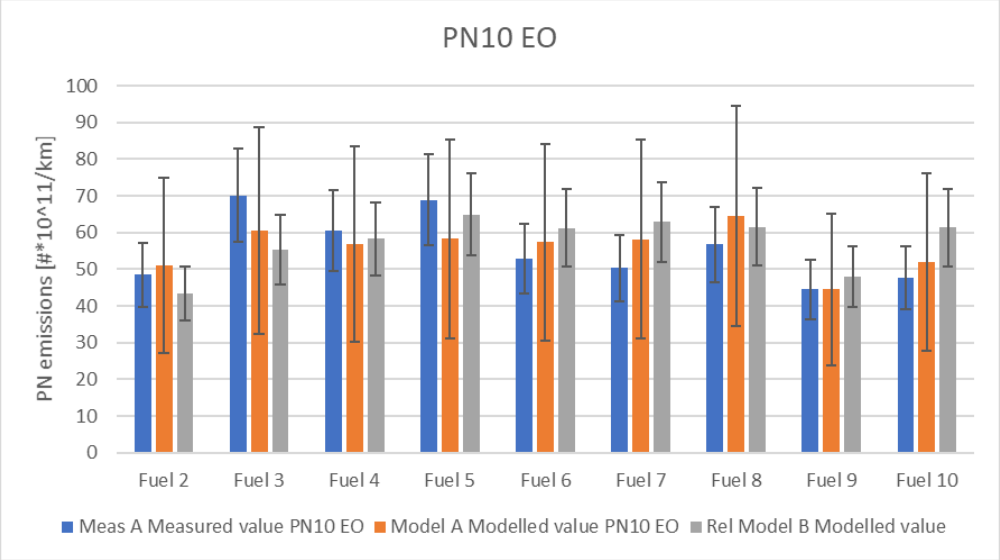


Figure 17.31 Transferring modelling results from other vehicles (PN_{10} EO)

Equally for PN_{23} EO, the relative model created from vehicle B model was seen somewhat satisfactory as seen in ***Figure 17.32***. Greatest deviation was found for

fuels 4, 5 and 6, which typically underpredicted the PN emissions compared to the experimental results. The relative model did not seem to overestimate any PN_{23} EO emissions apart from for fuel 10.

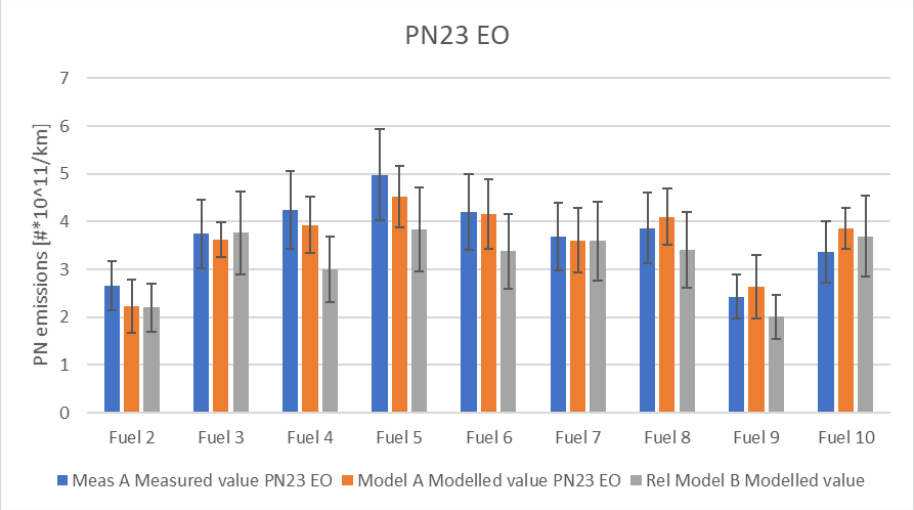


Figure 17.32 Transferring modelling results from other vehicles (PN_{23} EO)

The PN_{10} TP emissions estimated from the relative model were found evidently inconsistent for certain fuels, as shown in ***Figure 17.33***. The model underestimates significantly the PN output for fuels 2, 9 and 10 and overestimates the results for fuel 8. It should be noted that the PN_{10} TP emissions obtained for vehicle A were generally very low, hence the prediction of the output using data from a vehicle with a non-similar fuel response in the TP is very challenging.

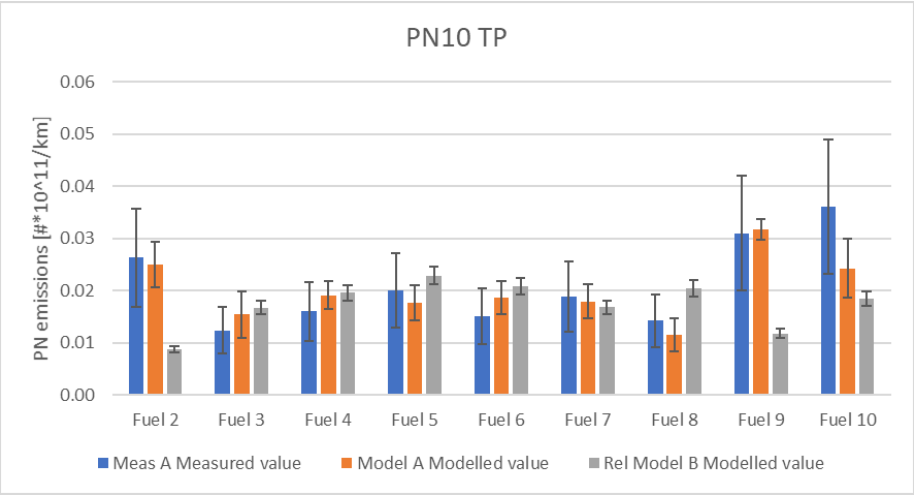


Figure 17.33 Transferring modelling results from other vehicles (PN_{10} TP)

Similarly, to PN_{10} TP results, the response for PN_{23} TP emissions predicted with the relative model was found rather poor (***Figure 17.34***). This conclusion was however fairly expected as no reasonable correlation between fuel properties or any accurate equation for the PN_{23} TP emissions were even found by using the vehicle A input data.

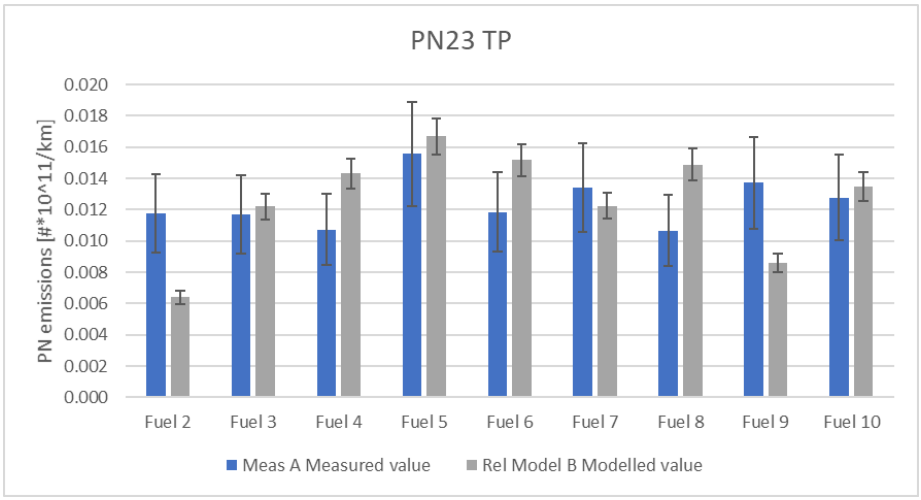


Figure 17.34 Transferring modelling results from other vehicles (PN_{23} TP)

Finally, ***Figure 17.35*** summarizes the correlation between the experimental PN data and the vehicle specific and relative model created for vehicle A. As concluded previously, the fuel response on PN EO emissions was found more comparable for the GDI vehicles than the PN TP emissions, which directly reflects to the cross-modelling potential. As the characteristics of PN TP emissions were proven to be highly dependent on the GPF characteristics, no reasonable vehicle to vehicle conclusion could be conducted. The overall correlation between the studied vehicles PN TP emissions were therefore concluded poor.

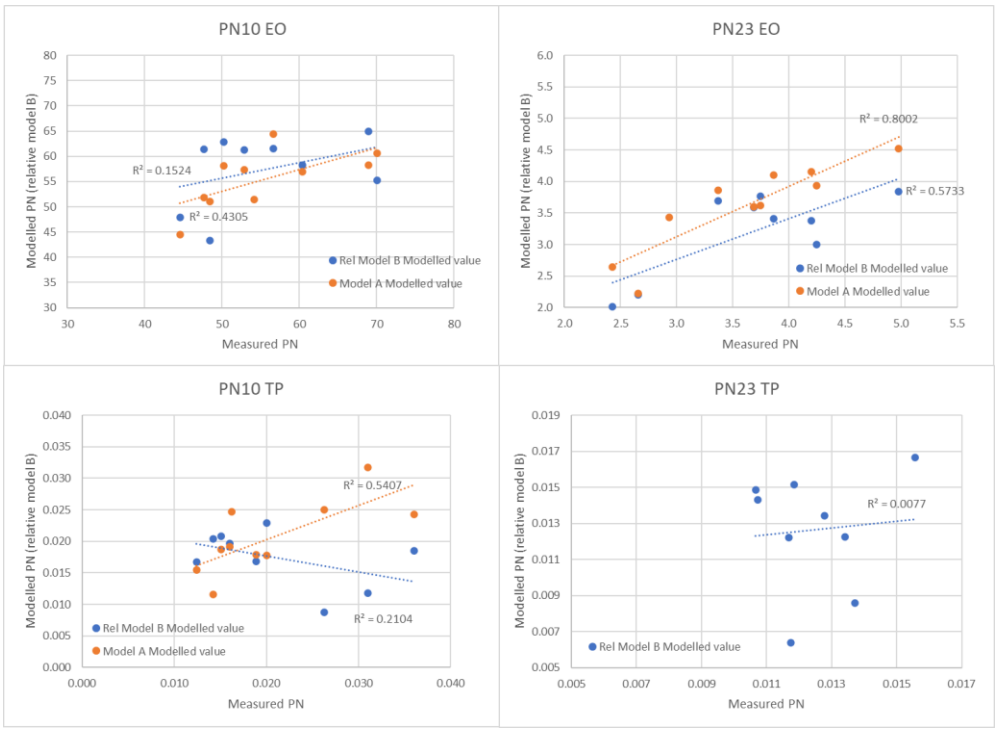


Figure 17.35 Correlation between the relative model created from vehicle B data and the measured vehicle A PN data

17.6. CHALLENGES, ISSUES AND UNCERTAINTIES

Initially, some of the experimentally obtained PN data sets were influenced by a relatively great trend behaviour which needed to be corrected. Additionally, the share of pure error for some of the data sets were found still relatively high even after correction. This created challenges especially in terms of model fitting. This could be seen in the model outputs as the trend slope did not perfectly correlate with ideal bisector. The models created for e.g. vehicle B could however be successfully adjusted. Despite the trend corrections do improve the correlation and slope between measured and modelled results, a bias in the fuel effect may be carried out from the data input collected from the experimental data. This effect was seen quite evidently because the correlation between individual fuel properties was not found as high as desired even for the trend corrected data. The model output was therefore seen to over- or underpredict the PN emissions for certain PN emissions, especially for PN EO. The robustness of the modelling input data should be very high to model accurately any (PN) emissions. This is evidently not the case for all modern SI vehicles as the emission performance is influenced by several factors that contribute to PN deviation or other error factors. This may mean that two repetitions per fuel is insufficient to contribute robust data for accurate PN modelling (although nothing proves that better models could have been obtained with more repeats).

17.7. MODELLING SUMMARY

It can be concluded that the modelling of PN emissions for SI-vehicles is relatively challenging. One of the main reasons for this is that the fuel response was found relatively unequal for any of the vehicles tested in this study. Another challenge for the modelling process was concluded by high deviation and uncertainties originating from the experimental data. Furthermore, the magnitude of PN emissions both in terms of EO and TP vary significantly between vehicle to vehicle, and even the relative effect for absolute fuel response seems to be somewhat vehicle dependent. The greatest differences in fuel response were found, as expected, between GDI and PFI technologies. The vehicles with GDI technology responded relatively similarly in terms of PN EO emissions. However, no decisive relation between fuel response to TP emissions between the tested vehicles was found. This was concluded to be caused by the differences in GPF characteristics, which were determined unequal even between the two GDI vehicles. E.g., the PN TP emissions for vehicle A were found extremely low. As no significant correlation between PN_{23} TP emissions and fuel properties was found for vehicle A, no model for PN_{23} was developed.

From the three tested vehicles, the models created for vehicle B with the corrected PN input data were concluded most reliable. The model created for vehicle B from the corrected PN data was concluded robust and the modelled output was generally within the determined uncertainties carried over from the measured data. The models created for vehicle B by using trend corrected data corresponded furthermore better with the trends for the experimental values. The extremely low PN TP emissions for vehicle A may explain the poor modelling potential for the given application.

The input variables used for vehicle C models were not in line with the two GDI vehicles. The fuel response obtained by modelling was therefore not directly proportional with any of the GDI vehicles. The models created for vehicle C were additionally found not predictive, meaning that any changes in fuel properties would be difficult to predict with any of the PN models. Despite the fit and correlation between experimental and modelled PN_{10} EO emission data was found

satisfactory, the validation with two randomly selected fuels removed showed that the model is highly sensitive to the data input. The modelled data trends for the other PN emissions with vehicle C were overall poorly correlating with the measured data, making the usability of the PFI model highly questionable.

The cross-modelling potential was studied by calculating relative models. The relative models were calculated in respect to one nominated fuel, in this case, fuel 1. The results obtained by comparing the relative models suggest that the fuel response may in some extent be estimated for PN EO emissions between GDI vehicles. Yet again, due to the different characteristics of GPFs, correspondence between PN TP model output was found poor. As the magnitude of PN emission vary between vehicle to vehicle, no direct, absolute values may be predicted by one general cross-model. Furthermore, by comparing the modelling results obtained from phase 1 and phase 2, it may be concluded that model response created from different driving cycles are not directly transferrable either. However, some directional PN prediction could be made in some extent as the change in PN emissions in respect to e.g. phase 1 E150 x aromatics interaction model predicted were mostly coaxial.

18. PHASE 2 - SUMMARY AND CONCLUSIONS

The scope of this study was to examine the relationship between fuel properties of ten different petrol-based fuels and PN emissions. The study was conducted using three modern SI-vehicles. Two of the studied vehicles were equipped with GDI fuel injection, while the third vehicle represented a traditional PFI vehicle. All vehicles were equipped with GPFs. Eight market fuels, sampled from European refineries were tested on each of the vehicles. The fuel matrix was designed to vary different fuel properties such as E150, total aromatics and olefins content or ethanol content by targeting specific samples in the refineries, but without any specific intervention in the fuel design. Additionally, two fuels had to be specifically formulated to complete the fuel matrix. The range of variation of the fuel properties was selected to match the values seen in the EU FQD market survey. The content of this study was divided into two main parts, an experimental part where the vehicles were tested in an emission laboratory equipped with a chassis dynamometer. The second part was solely based on mathematical modelling, where the experimental results acquired from the study were transferred to MATLAB for further analysis and model development. The main objective for the modelling was to find relationships between fuel properties and PN emission formation. A model for each PN emission was created based on the experimental data. The vehicles were tested using a test cycle simulating RDE conditions. The RDE test cycle was adopted from a real life PEMS test that is being used by VTT in the Espoo region, located in Finland. To correspond better with real life conditions, the ambient temperature of the chassis dynamometer environment was set to 12 °C. During the laboratory tests, both gaseous and particulate EO and TP emissions were sampled. The particulate sampling included continuous PN_{10} and PN_{23} sampling with CPCs both as EO and TP. Furthermore, PM emission were collected in TP in form of gravimetric filter sampling over four test phases.

A relatively great variation in the response of the different vehicles towards the fuels properties was observed. The magnitude of PN10 EO emissions for the two GDI vehicles were found relatively similar, and the PFI equipped vehicle, vehicle C, produced lower PN10 EO emissions. However, the magnitude of PN23 EO emissions was found similar between vehicles A and C and the PN23 EO emissions were significantly higher for the second GDI vehicle (vehicle B). Furthermore, the filtration efficiency of vehicle A's GPF was found fairly high, resulting in extremely low PN TP emissions overall. This was not as much the case for vehicle B, which produced higher PN TP emissions compared to the other two test vehicles. Even if the PFI vehicle (vehicle C) was also equipped with a GPF, vehicle A still produced lower PN TP emissions although GDI technology is typically expected to produce more PN emissions than PFI technology. In an attempt to better understand the potential impact of fuels properties on GPF's filtration efficiency, correlations between EO and TP emissions were studied as a function of fuels. However, this showed no consistent response, as some fuels increasing the EO PN emissions could decrease the TP PN emissions, and vice-versa. Furthermore, in order to improve the understanding of the fuel response of the three test vehicles, the correlation between each vehicle's PN emissions was also studied. It showed that there was no correlation between the PN emissions of the three test vehicles. It means that each vehicle's PN emissions react differently (and sometimes in opposite directions) to a given modification of fuels physical-chemical properties. These observations have important consequences: they imply that it is not possible for the fuel producer to design a fuel that simultaneously reduces the PN emissions in all vehicles.

With the direct data collected, no accurate fuel-related modelling was possible due to strong temporal trend behaviour of PN emissions for vehicles A and C. For these

vehicles, it was observed that the PN emissions measurements of the reference fuels shifted over time throughout the test campaign. For this reason, the data was corrected by normalizing against repeat of the reference fuel in an attempt to (successfully) improve the results repeatability. Despite effective corrections were applied, relatively large error or noise for some of the PN data remained. Vehicle B was found to be less subject to measured temporal deviation and more repetitive throughout the test campaign. The most significant PN influencing factors found during the analysis for vehicle B were aromatics content and vapour pressure (DVPE), which were found to increase PN emissions, while fuels with a lower yield in the early distillation curve (IBP to 50% vol) or a lower E70 tend to decrease PN emissions (or in other words, fuels having a bigger light fraction tend to increase vehicle B's PN emissions). For Vehicle A, similar conclusions were drawn for PN23 EO, but no satisfying model could be obtained for PN TP nor for PN10 EO. For vehicle C, the correlations were poor and the effect of fuel properties on PN emissions could not be identified. Overall, the PN models created for vehicles A and C were found inaccurate while the PN models generated for vehicle B resulted in relatively robust and accurate output. The validation of the vehicle B's models suggests that these models are predictive for this vehicle, such as demonstrated by removing two fuels from the input data and successfully predicting the measured PN values without prior calibration of the model on these measurements.

During the comparison of the generated PN models two key findings may be concluded. First, despite a relatively accurate, vehicle specific PN model is producible, the model may not necessary be transferrable for predicting the PN emissions for other vehicles. This is mostly due to differences in the vehicle specific fuel response. As a result, any vehicle to vehicle cross-modelling was concluded somewhat inaccurate. One of the main reasons is that any uniform principles for PN formation does not seem to fully exist, and e.g., the characteristics of vehicle injection technology and GPF influence greatly the outcome of PN TP emissions. Additionally, to generate a PN model producing reliable, absolute predictions is challenging if the data set is limited because the contribution of natural noise and error caused in experimental tests may decrease the accuracy significantly. Secondly, a PN model developed from data produced with a test vehicle, test method or condition that is not directly comparable with PN models produced with non-comparable conditions. Despite the magnitude of the PN emissions between different conditions may be addressed by calculating relative changes, the model output may vary significantly due to other variables.

SECTION 5

OVERARCHING CONCLUSION

19. OVERARCHING CONCLUSION

Between 2019 and 2022, Concawe conducted a research programme examining the relationship between gasoline physical-chemical properties and particulates numbers (PN) emissions. The programme was executed in two distinct phases, during which 4 vehicles using 23 fuels were tested in emission laboratories equipped with a chassis dynamometer. All the combinations of vehicles and fuels tested showed tailpipe PN emissions compliant with the latest Euro 6d standards. For each phase, mathematical models were developed to examine the link between fuel properties and experimentally measured PN emissions.

The results from each phase are inconsistent with each other from a "fuel design" point of view. Additionally, it was not possible to predict the PN emissions of a given vehicle using the PN model elaborated from the other vehicle.

This suggests that it is difficult to identify a set of fuel parameters, which could be part of EN228, that would consistently decrease the PN emissions in all operations across all vehicles.

During the first phase, 13 formulated fuels (surrogates) were tested on a single vehicle equipped with a gasoline direct injection (GDI) engine and a gasoline particulate filter (GPF). The fuel matrix was designed to intentionally and independently vary different fuel properties suspected to impact PN emissions (according to the literature): volume evaporated at 150°C (E150) as a proxy of the heavy fraction of gasoline, total aromatics content, heavy aromatics content (more than 9 carbons) and ethanol content. The vehicle was tested using an "ambient start" (23°C) WLTC (Worldwide harmonized Light vehicle Test Cycle), a "hot start" WLTC and a test cycle simulating RDE (Real Driving Emissions) conditions. During the laboratory tests, both gaseous and particulate engine-out (EO) and tailpipe (TP) emissions were sampled. The particulate sampling included continuous PN10 and PN23 (PN having a diameter respectively bigger than 10 nm and 23 nm). In this first phase, it was concluded that it was possible to establish a fairly good and simple model between TP PN emissions and the fuel properties targeted in the fuel matrix, and more particularly E150 and total aromatics content. The experimental data was also used to check the correlation to other PN models referenced in the literature: "Honda PM Index", "Yield Sooting Index" (YSI), simplified PM index (based on E130 and E170) or simple correlation with E150. It was found that none of these models correlate with the experimental data collected, showing the incapability of these literature models to actually predict PN emissions from the test vehicle on which they were not calibrated.

These two results demonstrate that, on one hand, it was easy to establish a simple model based on only two simple parameters such as E150 and total aromatics content; and on the other hand, it was impossible to find any correlation with any other existing PN models, including more complex ones. This conflict raised two fundamental questions on what was done during the first phase of the study:

- Would the models developed on the tested vehicle be valid on other vehicles?

- Would the models developed on the tested fuel matrix composed of surrogates be also valid on a fuel matrix composed of real market fuels?

These questions triggered the second phase of this study. This time, the study was conducted on three vehicles. Two of the studied vehicles were equipped with GDI technology (vehicles A and B), while the third one (vehicle C) was equipped with a

port fuel injection (PFI) engine. All of them were equipped with GPFs. Eight market fuels, sampled from European refineries, were tested on each of the vehicles. The fuel matrix was designed to vary different fuel properties such as E150, total aromatics and olefins content or ethanol content by targeting specific samples in the refineries, but without any specific intervention in the fuel design. Additionally, two fuels had to be specifically formulated to complete the fuel matrix, reaching a total of ten fuels. The range of variation of the fuel properties was selected to match the values seen in the EU FQD market survey. This second phase followed a similar structure as the first one:

- an experimental part for the purpose of vehicles testing with an experimental setup similar to the first phase (using a different RDE cycle and with a cold start at 12°C to be representative of average real-world conditions in Europe);

- a modelling part, focused mainly on relationships between fuel properties and PN emissions with a specific part on vehicles cross-comparisons regarding their fuel response.

In the second phase, a relatively great variation in how the different vehicles responded to the fuels properties was observed. The magnitude of PN10 EO emissions for the two GDI vehicles were found relatively similar, and the PFI equipped vehicle, vehicle C, produced lower PN10 EO emissions. However, the magnitude of PN23 EO emissions was found similar between vehicles A and C and the PN23 EO emissions were significantly higher for the second GDI vehicle (vehicle B). Furthermore, the filtration efficiency of vehicle A's GPF was found fairly high, resulting in extremely low PN TP emissions overall. This was not as much the case for vehicle B, which produced higher PN TP emissions compared to the other two test vehicles. Although the PFI vehicle (vehicle C) was also equipped with a GPF, vehicle A still produced lower PN TP emissions although GDI technology is typically expected to produce more PN emissions than PFI technology. In an attempt to better understand the potential impact of fuels properties on GPF's filtration efficiency, correlations between EO and TP emissions were studied as a function of fuels. Unfortunately, this showed no consistent response, as some fuels increasing the EO PN emissions could decrease the TP PN emissions, and vice-versa. Furthermore, in order to improve the understanding of the fuel response of the three test vehicles, the correlation between each vehicle's PN emissions was also studied. It showed that there was no correlation between the PN emissions of the three test vehicles. It means that each vehicle's PN emissions react differently (and sometimes in opposite directions) to a given modification of fuels physical-chemical properties. These observations have important consequences: they imply that it is not possible for the fuel producer to design a fuel that simultaneously reduces the PN emissions in all vehicles.

With the direct data collected, no accurate fuel-related modelling was possible due to strong temporal trend behaviour of PN emissions for vehicles A and C. For these vehicles, it was observed that the PN emissions measurements of the reference fuels shifted over time throughout the test campaign. For this reason, the data was corrected by normalizing against repeat of the reference fuel in an attempt to (successfully) improve the results repeatability. Despite effective corrections were applied, relatively large error or noise for some of the PN data remained. Vehicle B was found to be less subject to measured temporal deviation and more repetitive throughout the test campaign. The most significant PN influencing factors found during the analysis for vehicle B were aromatics content and vapour pressure (DVPE), which were found to increase PN emissions, while fuels with a lower yield in the early distillation curve (IBP to 50% vol) or a lower E70 tend to decrease PN emissions (or in other words, fuels having a bigger light fraction tend to increase

vehicle B's PN emissions). For Vehicle A, similar conclusions were drawn for PN23 EO, but no satisfying model could be obtained for PN TP nor for PN10 EO. For vehicle C, the correlations were poor and the effect of fuel properties on PN emissions could not be identified. Overall, the PN models created for vehicles A and C were found inaccurate while the PN models generated for vehicle B resulted in relatively robust and accurate output.

During the comparison of the PN models generated for each vehicle, it was found that a relatively accurate PN model could be obtained specifically on vehicle B, however, this model does not fit with the results of other test vehicles. This is mostly due to differences in the vehicle specific fuel response, e.g. because of the characteristics of vehicle injection technology, strategy and GPF filtration efficiency that greatly impacts the outcome of PN TP emissions. As a result, any vehicle-to-vehicle cross-modelling was found to be inconsistent (within vehicles of Phase 2, tested in the same conditions, and also across vehicles of the first and second phase, tested in different conditions).

Overall, it was impossible to design a consistent TP or EO PN model based on fuel properties across the different vehicles and powertrains. However, it was possible to elaborate individually accurate PN emissions models based on the fuel properties for two of the vehicles tested in the whole test programme (phase 1 and 2 together), but it was impossible to obtain any satisfying model for the two other vehicles. It is noteworthy that the two vehicles for which it was possible to elaborate PN models are different, tested in slightly different driving conditions, but made by the same OEM and equipped with the same engine. The models obtained on each of these two vehicles are significantly different: while they both indicate that an increased content of aromatics tends to increase PN emissions, one of the models indicates a stronger correlation with the high boiling end of the distillation curve, conversely the other model indicates a stronger correlation with the light end of the distillation curve.

Appendix A

Property	Units	Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Fuel 6	Fuel 7	Fuel 8	Fuel 9	Fuel 10
Type	-	UL95-E10	UL98-E5	UL98-E5	Splash blend E10	Splash blend E10	Splash blend E20	UL95-E5	UL95-E10	UL95-E5	UL95-E5
RON	-	97.2	99.6	99.1	96.7	97.2	99.8	-	96.5	95.1	95.2
MON	-	85.6	89.7	87.2	85.0	84.9	86.1	-	85.7	85.6	85.0
Density	kg/m3	747.8	744.6	759.4	747.0	752.0	756.6	747.4	748.6	753.3	757.4
IBP	◦C	35.5	35.7	29.5	31.9	31.0	31.6	31.1	27.0	40.0	35.2
-- 5% vol	◦C	52.4	58.5	45.9	-	-	-	44.0	38.3	-	-
-- 10% vol	◦C	56.1	66.6	53.0	48.3	46.5	47.9	51.2	44.5	56.3	51.5
-- 20% vol	◦C	60.6	76.4	64.2	43.9	53.0	55.3	61.3	53.0	60.3	56.9
-- 30% vol	◦C	64.9	84.9	73.5	59.2	58.4	61.2	71.4	60.6	70.8	63.4
-- 40% vol	◦C	78.7	92.6	81.7	63.9	62.8	66.1	82.8	66.7	89.6	81.2
-- 50% vol	◦C	97.3	100.4	90.0	71.0	67.2	70.2	96.2	74.5	104.4	104.9
-- 60% vol	◦C	109.6	108.0	99.3	103.8	95.5	73.7	110.4	109.0	115.3	120.8
-- 70% vol	◦C	120.7	116.2	110.4	122.0	118.2	88.9	124.1	122.9	126.7	133.4
-- 80% vol	◦C	131.4	125.7	124.9	140.0	133.1	130.1	138.7	135.6	149.4	148.7
-- 90% vol	◦C	145.8	142.8	148.3	162.3	146.7	144.4	157.6	151.9	168.7	164.9
-- 95% vol	◦C	155.3	156.5	165.1	178.2	155.8	153.7	171.8	163.4	175.4	174.0
FBP	◦C	181.1	192.0	187.9	198.9	172.5	171.2	201.0	186.4	190.7	189.2
E70	%v/v	35.8	13.2	26.0	49.7	52.1	49.5	28.7	47.4	29.4	34.5
E100	%v/v	51.8	49.7	60.5	58.4	61.5	71.0	52.7	56.6	46.7	47.8
E150	%v/v	92.2	92.7	90.5	84.8	92.0	92.8	86.4	89.2	80.2	80.7
DVPE	kPa	52.5	41.7	63.5	69.7	76.4	74.7	62.8	83.4	48.5	56.8
Olefins	%v/v	12.4	2.3	4.0	12.9	8.3	7.3	7.4	7.0	10.5	10.7
Aromatics	%v/v	27.8	22.0	34.4	28.4	35.0	31.4	33.1	31.6	20.5	33.9
C9 and C9+ aromatics	%v/v	7.8	7.3	12.0	12.5	9.9	8.9	12.5	11.9	5.5	9.8
<C9 Aromatics	%v/v	20.1	14.7	22.4	15.9	25.1	22.5	20.5	19.7	15.0	24.1
Oxygen	%m/m	3.6	2.6	2.6	3.7	3.8	7.4	0.9	3.7	2.7	2.7
Ethanol	%v/v	7.9	0.0	0.2	9.9	10.2	19.3	0.0	9.7	5.1	5.3
ETBE	%v/v	7.3	17.7	18.8	0.0	0.0	0.0	0.1	0.0	5.1	5.0
MTBE	%v/v	0.2	0.0	0.0	0.0	0.1	0.0	4.9	0.5	0.0	0.0
LHV	MJ/kg	41.5	42.0	41.7	41.8	41.5	39.9	42.9	41.6	41.8	41.4
Carbon content	%m/m	82.8	83.3	84.5	83.0	83.3	79.7	85.8	83.1	83.9	84.4
Hydrogen content	%m/m	13.6	14.0	12.9	13.4	13.0	12.9	13.3	13.2	13.5	12.9
Oxygen content	%m/m	3.6	2.6	2.6	3.7	3.8	7.4	0.9	3.7	2.7	2.7

Appendix B

Uncorrected emission resutls

	Vehicle A		Vehicle B		Vehicle C	
RDE-cycle	Mean	Mean deviation	Mean	Mean deviation	Mean	Mean deviation
CO2 TP		(g/km)		(g/km)		(g/km)
Fuel 1	110	1.53	105	0.97	103	1.98
Fuel 2	110	2.45	104	0.71	101	0.61
Fuel 3	112	0.66	108	5.53	105	1.18
Fuel 4	110	0.59	104	0.54	103	0.81
Fuel 5	112	2.91	107	1.10	104	1.07
Fuel 6	111	2.64	106	0.99	103	0.56
Fuel 7	112	1.52	107	1.98	105	0.57
Fuel 8	110	0.39	106	2.77	104	0.67
Fuel 9	109	0.73	107	0.22	104	1.59
Fuel 10	112	1.32	108	1.80	105	0.76
CO TP		(g/km)		(g/km)		(g/km)
Fuel 1	0.02	0.003	0.30	0.027	0.07	0.014
Fuel 2	0.03	0.004	0.29	0.009	0.07	0.016
Fuel 3	0.03	0.004	0.34	0.061	0.08	0.015
Fuel 4	0.02	0.007	0.24	0.019	0.08	0.021
Fuel 5	0.02	0.004	0.28	0.021	0.08	0.019
Fuel 6	0.02	0.005	0.25	0.034	0.05	0.018
Fuel 7	0.03	0.005	0.32	0.019	0.07	0.012
Fuel 8	0.02	0.000	0.26	0.010	0.09	0.029
Fuel 9	0.02	0.000	0.28	0.000	0.07	0.004
Fuel 10	0.02	0.002	0.33	0.064	0.09	0.011
NOx TP		(g/km)		(g/km)		(g/km)
Fuel 1	0.011	0.0007	0.006	0.0003	0.009	0.0002
Fuel 2	0.010	0.0006	0.006	0.0002	0.009	0.0007
Fuel 3	0.012	0.0010	0.006	0.0003	0.023	0.0126
Fuel 4	0.012	0.0006	0.007	0.0001	0.011	0.0042
Fuel 5	0.012	0.0002	0.006	0.0003	0.012	0.0056
Fuel 6	0.013	0.0011	0.007	0.0002	0.022	0.0143
Fuel 7	0.013	0.0013	0.005	0.0003	0.008	0.0001
Fuel 8	0.011	0.0004	0.007	0.0003	0.011	0.0017
Fuel 9	0.009	0.0029	0.006	0.0003	0.010	0.0004
Fuel 10	0.011	0.0001	0.006	0.0013	0.010	0.0000
THC TP		(g/km)		(g/km)		(g/km)
Fuel 1	0.008	0.0023	0.013	0.0031	0.011	0.0011
Fuel 2	0.019	0.0026	0.013	0.0010	0.012	0.0008
Fuel 3	0.008	0.0189	0.012	0.0021	0.013	0.0015
Fuel 4	0.006	0.0044	0.010	0.0019	0.012	0.0023
Fuel 5	0.006	0.0008	0.012	0.0005	0.012	0.0020
Fuel 6	0.007	0.0004	0.010	0.0015	0.011	0.0017
Fuel 7	0.006	0.0007	0.013	0.0014	0.011	0.0017
Fuel 8	0.005	0.0004	0.010	0.0008	0.013	0.0024
Fuel 9	0.005	0.0004	0.012	0.0002	0.012	0.0018
Fuel 10	0.008	0.0003	0.012	0.0011	0.019	0.0000

Uncorrected emission resutls						
	Vehicle A		Vehicle B		Vehicle C	
PN10 EO	(#*10^11/km)		(#*10^11/km)		(#*10^11/km)	
Fuel 1	85.5	66.1	31.6	5.5	12.9	2.9
Fuel 2	85.4	76.1	32.2	0.9	13.4	1.2
Fuel 3	50.1	19.9	40.1	10.9	14.9	2.2
Fuel 4	42.7	6.7	44.8	6.4	28.9	0.8
Fuel 5	51.3	1.3	41.3	5.6	18.3	7.6
Fuel 6	73.9	30.4	52.7	40.2	14.7	0.5
Fuel 7	60.4	12.0	55.1	10.9	21.7	4.0
Fuel 8	52.5	20.6	48.8	3.0	22.2	2.7
Fuel 9	42.9	7.8	34.9	1.9	15.5	2.8
Fuel 10	50.9	7.0	54.8	3.2	21.2	1.1

PN23 EO	(#*10^11/km)		(#*10^11/km)		(#*10^11/km)	
Fuel 1	3.07	1.03	9.91	3.66	2.66	0.15
Fuel 2	2.85	1.53	7.35	2.27	3.31	1.33
Fuel 3	3.63	0.43	13.10	1.68	3.82	0.88
Fuel 4	4.07	0.03	14.20	0.12	6.90	6.27
Fuel 5	4.90	0.54	16.13	2.43	3.25	1.33
Fuel 6	4.48	0.85	13.61	3.44	4.37	1.97
Fuel 7	3.87	1.09	17.71	2.64	5.06	1.67
Fuel 8	3.92	0.45	14.05	3.63	6.81	1.90
Fuel 9	2.49	0.15	9.68	3.55	3.11	1.00
Fuel 10	3.50	1.04	17.79	4.53	5.91	2.22

PN10 TP	(#*10^11/km)		(#*10^11/km)		(#*10^11/km)	
Fuel 1	0.04	0.026	0.74	0.038	0.09	0.024
Fuel 2	0.07	0.069	0.43	0.014	0.10	0.022
Fuel 3	0.02	0.003	0.83	0.234	0.12	0.060
Fuel 4	0.03	0.011	1.07	0.110	0.10	0.006
Fuel 5	0.03	0.004	1.08	0.066	0.09	0.018
Fuel 6	0.03	0.012	1.05	0.093	0.09	0.001
Fuel 7	0.03	0.008	0.89	0.146	0.11	0.052
Fuel 8	0.02	0.002	0.99	0.020	0.08	0.015
Fuel 9	0.05	0.042	0.59	0.121	0.09	0.015
Fuel 10	0.05	0.035	0.96	0.106	0.07	0.018

PN23 TP	(#*10^11/km)		(#*10^11/km)		(#*10^11/km)	
Fuel 1	0.02	0.006	0.67	0.098	0.06	0.021
Fuel 2	0.02	0.001	0.41	0.006	0.07	0.015
Fuel 3	0.01	0.003	0.73	0.142	0.06	0.014
Fuel 4	0.01	0.000	1.04	0.118	0.07	0.008
Fuel 5	0.02	0.004	1.05	0.069	0.06	0.012
Fuel 6	0.01	0.009	1.02	0.085	0.06	0.002
Fuel 7	0.01	0.001	0.84	0.138	0.07	0.034
Fuel 8	0.01	0.000	0.95	0.036	0.06	0.012
Fuel 9	0.02	0.006	0.55	0.077	0.07	0.014
Fuel 10	0.01	0.008	0.93	0.097	0.05	0.015

PM TP	(mg/km)		(mg/km)		(mg/km)	
Fuel 1	0.10	0.03	0.16	0.09	0.08	0.00
Fuel 2	0.29	0.31	0.17	0.00	0.26	0.00
Fuel 3	0.09	0.03	0.19	0.15	0.12	0.00
Fuel 4	0.16	0.00	0.09	0.03	0.18	0.00
Fuel 5	0.13	0.03	0.17	0.03	0.11	0.00
Fuel 6	0.08	0.02	0.16	0.08	0.09	0.00
Fuel 7	0.10	0.05	0.12	0.04	0.15	0.00
Fuel 8	0.10	0.02	0.03	0.16	0.08	0.00

Corrected emission resutls

	Vehicle A		Vehicle B		Vehicle C	
RDE-cycle	Mean	Mean deviation	Mean	Mean deviation	Mean	Mean deviation
CO2 TP	(g/km)		(g/km)		(g/km)	
Fuel 1	110.32	0.83	105.55	1.33	102.74	1.06
Fuel 2	109.88	1.09	104.22	0.02	101.77	0.48
Fuel 3	112.75	0.08	108.53	4.75	105.25	1.10
Fuel 4	110.92	0.08	103.75	0.27	102.95	0.07
Fuel 5	112.38	2.17	107.49	1.59	103.95	0.69
Fuel 6	110.67	2.35	106.17	0.22	103.87	0.31
Fuel 7	111.29	1.79	106.83	1.14	104.27	1.45
Fuel 8	110.29	0.42	105.36	1.44	104.58	0.07
Fuel 9	109.11	0.03	106.79	1.02	103.53	0.48
Fuel 10	111.57	1.59	107.50	3.23	105.03	0.74
CO TP	(g/km)		(g/km)		(g/km)	
Fuel 1	0.02	0.00	0.30	0.03	0.07	0.01
Fuel 2	0.03	0.00	0.28	0.00	0.07	0.01
Fuel 3	0.03	0.01	0.35	0.03	0.08	0.01
Fuel 4	0.02	0.00	0.24	0.00	0.08	0.02
Fuel 5	0.02	0.00	0.28	0.01	0.07	0.02
Fuel 6	0.02	0.00	0.25	0.01	0.06	0.02
Fuel 7	0.03	0.01	0.32	0.01	0.07	0.00
Fuel 8	0.02	0.00	0.26	0.01	0.09	0.03
Fuel 9	0.02	0.00	0.28	0.01	0.06	0.01
Fuel 10	0.02	0.00	0.33	0.04	0.09	0.02
NOx TP	(g/km)		(g/km)		(g/km)	
Fuel 1	0.011	0.0006	0.006	0.0002	0.011	0.0025
Fuel 2	0.011	0.0004	0.006	0.0003	0.008	0.0005
Fuel 3	0.012	0.0007	0.006	0.0005	0.022	0.0131
Fuel 4	0.012	0.0004	0.007	0.0003	0.010	0.0021
Fuel 5	0.012	0.0004	0.006	0.0002	0.012	0.0033
Fuel 6	0.013	0.0010	0.007	0.0000	0.018	0.0126
Fuel 7	0.012	0.0013	0.006	0.0004	0.011	0.0027
Fuel 8	0.011	0.0002	0.007	0.0004	0.010	0.0004
Fuel 9	0.009	0.0030	0.006	0.0004	0.010	0.0036
Fuel 10	0.011	0.0000	0.006	0.0012	0.010	0.0011
THC TP	(g/km)		(g/km)		(g/km)	
Fuel 1	0.006	0.0023	0.012	0.0031	0.011	0.0014
Fuel 2	0.005	0.0022	0.013	0.0006	0.012	0.0011
Fuel 3	0.014	0.0097	0.013	0.0004	0.013	0.0011
Fuel 4	0.005	0.0012	0.010	0.0008	0.012	0.0024
Fuel 5	0.006	0.0018	0.012	0.0002	0.012	0.0018
Fuel 6	0.008	0.0008	0.011	0.0004	0.011	0.0017
Fuel 7	0.010	0.0004	0.013	0.0009	0.011	0.0013
Fuel 8	0.007	0.0022	0.010	0.0002	0.013	0.0022
Fuel 9	0.007	0.0021	0.011	0.0000	0.012	0.0020
Fuel 10	0.007	0.0002	0.013	0.0007	0.019	0.0008

Corrected emission resutls						
	Vehicle A		Vehicle B		Vehicle C	
PN10 EO	(#*10^11/km)		(#*10^11/km)		(#*10^11/km)	
Fuel 1	54.2	16.8	37.0	10.1	12.7	0.5
Fuel 2	48.5	4.1	35.3	6.4	13.9	2.7
Fuel 3	70.1	28.6	42.1	10.3	15.3	0.4
Fuel 4	60.4	14.4	47.7	1.4	28.6	2.3
Fuel 5	68.9	11.5	49.2	10.2	17.0	5.4
Fuel 6	52.9	2.1	44.3	20.3	14.9	1.4
Fuel 7	50.3	6.4	51.5	8.7	21.4	0.6
Fuel 8	56.7	0.4	47.0	12.4	22.3	5.1
Fuel 9	44.6	13.9	37.7	11.1	15.4	5.1
Fuel 10	47.7	6.1	52.4	16.8	22.0	2.0

PN23 EO	(#*10^11/km)		(#*10^11/km)		(#*10^11/km)	
Fuel 1	2.93	0.77	10.49	3.67	3.30	1.77
Fuel 2	2.66	1.13	7.65	2.12	2.98	0.66
Fuel 3	3.74	0.31	13.00	3.40	3.55	0.03
Fuel 4	4.24	0.10	14.25	1.32	6.34	4.55
Fuel 5	4.98	0.76	16.58	1.52	3.60	1.39
Fuel 6	4.20	0.65	13.43	4.09	4.00	1.32
Fuel 7	3.69	1.15	16.94	2.90	5.96	1.36
Fuel 8	3.86	0.22	13.83	2.81	6.70	0.14
Fuel 9	2.43	0.28	10.13	3.53	3.40	0.35
Fuel 10	3.37	1.08	17.62	3.91	5.49	0.69

PN10 TP	(#*10^11/km)		(#*10^11/km)		(#*10^11/km)	
Fuel 1	0.02	0.007	0.74	0.029	0.09	0.008
Fuel 2	0.03	0.019	0.43	0.003	0.11	0.001
Fuel 3	0.01	0.001	0.83	0.248	0.12	0.033
Fuel 4	0.02	0.002	1.07	0.134	0.09	0.012
Fuel 5	0.02	0.006	1.07	0.051	0.08	0.005
Fuel 6	0.02	0.004	1.07	0.066	0.09	0.009
Fuel 7	0.02	0.002	0.88	0.121	0.11	0.008
Fuel 8	0.01	0.002	1.01	0.027	0.08	0.000
Fuel 9	0.03	0.025	0.59	0.105	0.09	0.008
Fuel 10	0.04	0.021	0.98	0.056	0.07	0.003

PN23 TP	(#*10^11/km)		(#*10^11/km)		(#*10^11/km)	
Fuel 1	0.01	0.003	0.67	0.088	0.06	0.001
Fuel 2	0.01	0.001	0.41	0.007	0.07	0.002
Fuel 3	0.01	0.002	0.72	0.169	0.07	0.001
Fuel 4	0.01	0.001	1.04	0.157	0.07	0.006
Fuel 5	0.02	0.002	1.04	0.045	0.06	0.001
Fuel 6	0.01	0.006	1.03	0.078	0.07	0.005
Fuel 7	0.01	0.000	0.82	0.121	0.07	0.005
Fuel 8	0.01	0.000	0.96	0.017	0.06	0.000
Fuel 9	0.01	0.004	0.55	0.060	0.07	0.004
Fuel 10	0.01	0.006	0.94	0.045	0.06	0.000

PM TP	(mg/km)		(mg/km)		(mg/km)	
Fuel 1	0.05	0.009	0.15	0.089	0.00	0.000
Fuel 2	0.12	0.116	0.16	0.029	0.00	0.000
Fuel 3	0.05	0.005	0.19	0.144	0.00	0.000
Fuel 4	0.09	0.022	0.08	0.023	0.00	0.000
Fuel 5	0.08	0.002	0.15	0.033	0.00	0.000
Fuel 6	0.06	0.003	0.17	0.053	0.00	0.000
Fuel 7	0.07	0.024	0.14	0.051	0.00	0.000
Fuel 8	0.07	0.009	0.01	0.172	0.00	0.000

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