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Comparison of particle emissions from advanced vehicles using DG TREN and PMP measurement protocols

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ABSTRACT

CONCAWE has developed extensive data on particle emissions from light-duty and heavy-duty vehicles through its previous experimental programmes. In this study, four light-duty vehicles, two diesel and two gasoline direct injection (GDI), were tested for particulate mass and particle number emissions under regulated (NEDC) and transient (Artemis) driving cycles. One of the two diesel vehicles was equipped with a Diesel Particulate Filter. Particle number emissions were compared using procedures that had been developed in two different studies: the procedure previously used in the DG TREN "Particulates" Consortium Study (2001) and a second that has been adopted for Euro 5b certification of new light-duty diesel vehicles based on results from the Particle Measurement Programme (PMP).

The particulate mass and particle number measurements compared favourably between the two studies on comparable vehicles, fuels, and driving cycles. A broad correlation was observed between particulate mass and particle number for all vehicles (both diesel and gasoline) over the NEDC. The particle number emissions from the two gasoline vehicles were about the same order of magnitude as those from the diesel vehicle equipped with a particulate filter. The particle number results showed no apparent dependence on fuel properties even with significant variations in fuel sulphur level and other properties.

KEYWORDS

Exhaust emissions, diesel fuel, petrol, motor gasoline, engine technology, vehicles, fuel quality, Euro-3, Euro-4, Euro-5, particulate mass (PM), particle number (PN), carbonaceous particles, nucleation mode, accumulation mode, Particulate Measurement Programme (PMP)

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SUMMARY

As a contributor to the 2001 DG TREN “Particulates” Consortium, CONCAWE has developed extensive data on particle emissions from light-duty and heavy-duty vehicles.

More recently, the “Particle Measurement Programme” (PMP) Working Group, under the auspices of the United Nations Economic Commission for Europe (UNECE) Working Party on Pollution and Energy (GRPE) has developed alternative measurement methods for particulate mass (PM) and particle number (PN) compared to those that had previously been used in the DG TREN Consortium study. The PMP method for measuring total carbonaceous particles has now been validated in a number of testing laboratories on light-duty vehicles. This method was developed with the intention to complement vehicle tailpipe PM measurements with carbonaceous particle number measurements in the Euro 5 vehicle certification standards. The new PM standards and measurement method will apply to new light duty diesel vehicles beginning in September 2009. New light-duty diesel vehicles will be required to meet Euro 5b PN emissions standards in September 2011 and is also expected to apply to new gasoline direct injection (GDI) engines at a later date.

Using the PMP methods, four vehicles were tested in this PMP Follow-up study: two advanced technology light-duty diesel vehicles and two gasoline direct-injection (GDI) vehicles. One of the diesel vehicles, equipped with an additive-regenerated Diesel Particulate Filter (DPF), was the same vehicle that had been tested in CONCAWE’s previous work within the DG TREN Consortium. The current study was completed in order to extend our existing database of PM and PN measurements and to compare different measurement methods for PN emissions on comparable vehicles, fuels, and driving cycles.

The results show that both PM and PN measurements compared favourably between this PMP Follow-up study and the 2001 DG TREN “Particulates” programme on comparable vehicles, fuels, and driving cycles. A good correlation between PM and PN was observed for all vehicles (both diesel and gasoline) over the NEDC and the Artemis Motorway cycle, with the exception of the DPF-equipped diesel vehicle. The PN emissions from the two GDI cars were about the same order of magnitude as those from the DPF-equipped diesel vehicle. The PN results showed no apparent dependence on fuel properties even with significant variations in fuel sulphur level and other properties.

1. INTRODUCTION

The accurate measurement of automotive particle emissions continues to be of considerable interest within the regulatory environment. Particles from vehicles and from other sources are now accepted as having an impact on air quality and on human health [1,2]. Despite extensive studies, however, the mechanisms by which ultrafine particles impact human health are still uncertain, although there are several hypotheses that attempt to explain the relationship between particle parameters and health impacts.

The introduction of clean fuels and advanced vehicle and after-treatment technologies has resulted in a substantial reduction in automotive particulate mass (PM) emissions [3,4] with a corresponding improvement in air quality. This reduction in PM emissions, however, has also made the remaining low levels of particle emissions increasingly difficult to practically measure (with vehicle compliance regulations still based on PM). For this reason, considerable work has been undertaken internationally to address improved measurement techniques [5], either by modifying filter procedures for mass measurement (PM) or by introducing a new metric for ultrafine particles (PN).

Over the past decade, many studies [6,7,8] have investigated different techniques and measurement protocols for ensuring the repeatable measurement of particle number emissions. It is now generally accepted that automotive particle emissions fall into two broad categories [9]:

- "Nucleation" mode particles, generally less than about 30 nm particle size, comprising predominantly condensed volatile material, mainly sulphates and heavy hydrocarbons, and
- "Accumulation" mode particles, mainly carbonaceous in nature and larger than about 30 nm particle size.

Previous work [7] has shown that accumulation mode particles are rapidly formed in the engine exhaust and can be repeatably measured. Their size distribution is relatively unaffected by changes in the imposed measurement conditions. Nucleation mode particles, on the other hand, vary greatly with small changes in measurement procedures and can take time to stabilise before they can be reproducibly measured. Because of these effects, measurement artefacts are more likely to interfere with the measurement of nucleation mode particles unless special precautions are taken.

As reported in 2001, the DG TREN "Particulates" Consortium [10] addressed issues related to the formation and measurement of both nucleation and accumulation mode particles under different conditions and provided a harmonised particulate sampling and measurement methodology. Within this test work, accumulation mode particles were measured using an Electrical Low Pressure Impactor (ELPI) after volatile material had been removed from the particles by passing them through a Thermal Denuder (TD).

This methodology was applied in the DG TREN programme to quantify the effects of fuel properties and vehicle technology changes on both nucleation and accumulation mode particles. This work resulted in an improved understanding and knowledge of particle emissions, as well as a substantial database of validated data, and included measurements over a wide range of test cycles. CONCAWE's work within the DG TREN Consortium effort was published separately [9].

In addition to the DG TREN Consortium, an extensive “Particle Measurement Programme” (PMP) has also been carried out under the sponsorship of the UNECE GRPE [5]. The objective of this PMP programme on light-duty vehicles initially was develop and then validate a methodology to measure carbonaceous particles that could be used within the regulatory framework to certify the emissions performance of new vehicles. The methods tested included both particulate mass and carbonaceous particle number measurements. Accumulation mode carbonaceous particles were selected for the particle number measurements because they can be more repeatably sampled and measured while nucleation mode particles do not substantially contribute to particulate mass measurements.

Phase I of the PMP assessed a variety of measurement approaches and selected two (one particulate mass based and one particle number based) for further investigation in Phase II. The particulate mass method was based on the US 2007 filter procedure [11]. The particle number measurement used a novel approach to eliminate nucleation particles. For this measurement, a Constant Volume Sampling (CVS) system was used (in line with current regulatory requirements) and a sub-sample extracted from the CVS was subjected to rapid expansion in a hot evaporation tube. This approach rapidly reduces the partial pressure of the exhaust gas stream and ensures that any volatile material remains in the gas phase or, if already condensed on the carbonaceous particles, re-volatilizes into the gas phase before the particles are detected. Instead of the ELPI detector used in the DG TREN programme, a Condensation Particle Counter (CPC) is used to count the resulting “dry” carbonaceous particles.

This PMP procedure has led to revisions in both the light duty and heavy duty regulated measurement protocols [3,4] and the addition of particle number measurements to future light duty vehicle certifications [12]. It is expected that future light-duty vehicles will be assessed under this standard. A compliance limit of $6x10^{11}$ particles/km for light-duty diesel vehicles has been adopted in the EU’s Euro 5b technical regulation.

Phase III of the PMP focussed on a round robin exercise to assess this test procedure for carbonaceous particles [5]. A large number of testing laboratories participated in this round robin exercise which involved the measurement of exhaust emissions from a single vehicle (the “golden” vehicle) using a single piece of measurement equipment (the “golden” measurement system). Additional vehicles and alternative particle measurement equipment were also tested at the discretion of each testing laboratory for comparison to results obtained using the “golden” vehicle and the “golden” measurement system.

Following the PMP round robin exercise and the expected addition of this methodology into the legislative procedure, CONCAWE planned and conducted a work programme to measure particle emissions using these new procedures and to compare the results with the existing data from the DG TREN programme and from other testing [13].

One of the laboratories taking part in the PMP exercise was the same facility that CONCAWE had previously used to carry out its test work on the light-duty vehicle portion of the DG TREN “Particulates” Consortium. By using this laboratory and similar vehicles and fuels, there was an excellent opportunity to extend the data obtained from the DG TREN study and to directly compare the measurement of carbonaceous particles (i.e., particle number) using the PMP proposed procedure with existing CONCAWE data. The particle number measurement system used in this study was a recognised alternative to the “golden” measurement system but was not fully PMP compliant according to the system requirements specified at the

end of the PMP round robin exercise. The alternative measurement system used in this study is described in detail in Section 4.2.1.

Four vehicles were tested in the current study (also called the "PMP Follow-up" programme in this report): two advanced technology light-duty diesel vehicles and two gasoline direct-injection (GDI) vehicles. One of the two diesel vehicles was the same one that had previously been used in the DG TREN programme which permitted a direct comparison of measurement techniques on the same vehicle.

Three diesel fuels were tested in the current study:

- The 10ppm sulphur reference fuel that was used in the PMP test programme
- This same reference fuel doped with a sulphur-containing chemical reagent so that the sulphur content of the finished fuel was about 300ppm sulphur, and
- A Fischer-Tropsch (FT)[1] diesel fuel.

Two gasolines were also tested in two gasoline direct-injection (GDI) vehicles covering extremes of allowed fuel quality within the EN228 specification.

This report summarises the results obtained from this PMP Follow-up programme and compares the particulate mass (PM) and particle number (PN) measurements with data collected previously from the DG TREN "Particulates" programme. Results are reported for vehicles and fuels tested on the New European Driving Cycle (NEDC), Common Artemis Driving Cycles (CADC, also called Artemis), and three steady-state conditions at 50, 90, and 120 km/h.

[1] The **Fischer-Tropsch (FT) process** is a catalyzed chemical reaction that converts a synthesis gas mixture comprising carbon monoxide and hydrogen into hydrocarbon products. By adjusting the molecular weight and degree of isomerization, a Gas-to-Liquids (GTL) hydrocarbon liquid can be obtained having the qualities and characteristics of diesel fuel. To produce the GTL product used in this study, natural gas was used to create the synthesis gas mixture.

2. VEHICLE SELECTION

2.1.1. DIESEL VEHICLES

Two light-duty diesel vehicles were selected for the current study representing Euro 3 technologies available in the European market in 2006. These diesel vehicles were equipped with a medium sized direct injection engine with an oxidation catalyst (Vehicle E) and a large direct injection engine with an additive-regenerated Diesel Particulate Filter (DPF) system (Vehicle F).

In order to provide a direct comparison of measurement techniques, Vehicle F was the same one that had previously been used in the DG TREN "Particulates" study (Vehicle B).

Table 1 summarizes the technical characteristics of these diesel test vehicles.

Table 1 Technical Characteristics of the Light-duty Diesel Test Vehicles

Vehicle Characteristics	Units	Vehicle A[1]	Vehicle B[2,3]	Vehicle E	Vehicle F[2]
		DG TREN Study	DG TREN and Current Study	Current Study	DG TREN and Current Study
Displacement	cm^3	1896	2179	1896	2179
Maximum Power	kW @ rpm	74 @ 4000	98 @ 4000	103 @ 4000	98 @ 4000
Number of Cylinders		4	4	4	4
Maximum Torque	Nm @ rpm	240 @ 1800	314 @ 2000	320 @ 1750	314 @ 2000
Compression Ratio		19	17.6	18.5	17.6
Aspiration		Turbo Charged	Turbo Charged	Turbo Charged	Turbo Charged
Intercooler		Yes	Yes	Yes	Yes
Combustion Type		Direct Injection	Direct Injection	Direct Injection	Direct Injection
Injection System		Unit Injectors	Common Rail	Unit Injectors	Common Rail
Exhaust Gas Recirculation (EGR)		Yes	Yes	Yes	Yes
Exhaust After-treatment		Oxidation Catalyst	Additised Diesel Particulate Filter (DPF)	Oxidation Catalyst	Additised Diesel Particulate Filter (DPF)
Model Year	Year	2002	2001	2004	2001
Certification level		Euro-3	Euro-3	Euro-3	Euro-3

[2] From CONCAWE Report 1/05 [9]
[3] Vehicle B and Vehicle F were the same car

2.1.2. GASOLINE VEHICLES

Previous studies [9,14] have shown that gasoline direct injection (GDI) vehicles emit higher concentrations of ultrafine particles than conventional gasoline vehicles and that these particles exhibit chemical and physical characteristics that are more like particles emitted from diesel vehicles. For this reason, two GDI vehicles (Vehicles G and H) were also tested in the current study. These vehicles were newer versions of the same GDI vehicles that had previously been tested in the DG TREN "Particulates" study.

Table 2 summarizes the technical characteristics of these gasoline test vehicles.

Table 2 Technical Characteristics of the Light-duty Gasoline Test Vehicles

Vehicle Characteristics	Units	Vehicle C[4]	Vehicle D3	Vehicle G	Vehicle H
		DG TREN Study	DG TREN Study	Current Study	Current Study
Displacement	cm^3	1998	1997	2198	1598
Maximum Power	kW @ rpm	103 @ 5500	107 @ 6000	114 @ 5600	85 @ 5800
Inertia Class	kg	1250	1470	1535	1296
Number of Cylinders		4	4	4	4
Valves per Cylinder		4	4	4	4
Maximum Torque	Nm @ rpm	200 @ 4250	193 @ 4100	220 @ 3800	155 @ 4000
Compression Ratio		10.0 : 1	11.4 : 1	12.0 : 1	12.0 : 1
Combustion System		Stoichiometric	Lean	Stoichiometric	Lean and Stoichiometric
Injection System		Direct Injection (DI)	Direct Injection (DI)	Direct Injection (DI)	Direct Injection (DI)
Exhaust After-treatment		Three-Way Catalyst (TWC)	Three-Way Catalyst (TWC) plus NOx Trap	Three-Way Catalyst (TWC)	Three-Way Catalyst (TWC) plus NOx Trap
Model Year		2001	2002	2003	2004
Certification Level		Euro-3	Euro-3	Euro-3	Euro-4

[4] From CONCAWE Report 1/05 [9]

3. TEST FUELS

3.1. DIESEL FUELS

Three diesel fuels were selected for this programme. First, the reference fuel from PMP [5] was selected (Fuel DB) to reflect current EN590 quality. The second diesel fuel (Fuel DA) was produced by quantitatively adding a sulphur-containing reagent (di-(tertiary butyl)-di-sulphide) to Fuel DB so that the sulphur content of the finished fuel was about 300 ppm S. The third diesel fuel (Fuel DC) was an FT diesel fuel.

These fuels were selected because they were similar in composition to those used in the previous DG TREN study (Fuels D2, D4, and D8 in [10], see also **Appendix 1**).

Table 3 summarises the analytical results for Fuels DB and DC used in the current study. The sulphur content of Fuel DA, also called the “PMP+S” fuel in the current study, was measured to be 306 mg/kg S, using the ASTM D2622 test method.

With the exception of the sulphur content of Fuel DA, the analytical results for Fuel DB (PMP) and Fuel DA (PMP+S) shown in **Table 3** are as reported in **Appendix 2** of [5]. The sulphur content of Fuel DA and all of the analytical results for Fuel DC (the FT fuel) were measured at Shell Global Solutions using the indicated methods.

Before using these fuels for vehicle testing, the analytical properties were re-checked against the values shown in **Table 3** to confirm that the properties were as expected.

Table 3 Analytical Results for the Diesel Test Fuels

Fuel Property	Units	Test Method	PMP Fuel Fuel DB[1,2]	FT Fuel Fuel DC[3]
Cetane Number		EN ISO 5165	53.0	
		IP 498		82.8
Cetane Index		ASTM D4737	53.5	
		EN ISO 4264		90.4
Density	kg/m^3	IP 365/ASTM D4052	835	785
T50	°C	IP 123/ASTM D86	274	295
T95	°C	IP 123/ASTM D86	346	353
Final Boiling Point	°C	IP 123/ASTM D86	356	358
Flash point	°C	EN ISO 2719	75	101
CFPP	°C	EN116	-18	-1
Viscosity @ 40°C	mm^2/s	IP 71/ASTM D445	2.7	3.5
Total Aromatics	% m/m	IP 391	21.8	Typically <0.1[4]
Poly-Aromatics	% m/m	IP 391	4.4	Typically <0.1[4]
% Carbon	% m/m	GC	87.4[5]	
		ASTM D5291		85.0
% Hydrogen	% m/m	GC	11.4[5]	
		ASTM D5291		15.0
% Oxygen	% m/m	GC	<0.5[5][6]	==[6]
LHV	MJ/kg	ASTM D4868	43.36	
		ASTM D240/IP 12		44.06
Copper Corrosion 3h @ 50°C	Merit	IP 154/ASTM D130	1a	1a
Sulphur	mg/kg	EN ISO 4260 & EN ISO 8754	8	
		ASTM D2622		<5
Oxidation Stability	g/m^3	EN ISO 12205	10	3
Ash Content	% m/m	ISO 6245	<0.01	<0.01

(1) With the exception of the sulphur content, Fuels DA and DB were essentially identical in composition

(2) As reported in Appendix 2 of [5]

(3) Measured at Shell Global Solutions using the indicated test methods

(4) FT fuels typically have negligible aromatics content

(5) Measured using an in-house GC method

(6) No oxygenates were added to these diesel fuels

3.2. GASOLINE FUELS

Two gasoline fuels meeting EN228 specifications were also specially blended for this programme. Because the intent of this study was to examine extremes in properties within the EN228 specification, these fuels were not similar in composition to Fuels G1 and G2 evaluated in the DG TREN study (see also **Appendix 1**).

Table 4 summarises the analytical results for the gasoline fuels evaluated in the current study. All of the analytical results were measured at Shell Global Solutions using the indicated test methods.

Table 4 Analytical Results for the Gasoline Test Fuels

Fuel Property	Units	Test Method	Fuel GA	Fuel GB
Research Octane Number (RON)		ASTM D2699	98.0	96.1
Motor Octane Number (MON)		ASTM D2700	85.0	85.4
Density	kg/m^3	EN ISO 3675	772.5	736.4
DVPE	kPa	IP 394 EN 13016	50.2	66.3
E70	% v/v	EN ISO 3405	23.1	38.6
E100	% v/v	EN ISO 3405	46.9	63.9
E150	% v/v	EN ISO 3405	80.6	96.4
Final Boiling Point	°C	EN ISO 3405	204	168.1
Residue	% v/v	EN ISO 3405	1.3	1.2
Olefins	% v/v	GC(1)	16.29	6.5
Aromatics	% v/v	GC(1)	41.54	28.35
Benzene	% v/v	GC(1)	0.49	0.27
Sulphur	mg/kg	ASTM D2622	<3	5
Carbon	% m/m	GC(1)	87.58	86.55
Hydrogen	% m/m	GC(1)	12.42	13.95
Oxygen	% m/m	GC(1)	0(2)	0(2)

(1) Measured using an in-house modification of ASTM D6733 in which the initial temperature is 0°C.

(2) No oxygenates were added to these fuels.

3.3. LUBRICANT SELECTION

A common batch of lubricant was used for this programme in order to minimise effects from different lubricants. The lubricant was representative of current European lubricant quality, i.e. a good quality, high volume, conventional mineral oil formulation, meeting: SAE 15W-40, ACEA Class A3/B3 for light duty, ACEA Class E3 for heavy duty, with a sulphur content of 0.6% m/m.

4. TEST METHODOLOGY

4.1. TEST CYCLES AND DAILY PROTOCOL

Light duty vehicle tests were conducted by Shell Global Solutions and the following daily test sequence was used. (See also **Appendix 6**).

Light Duty Vehicle Test Sequence

- Fuel change
- Conditioning : Diesel cars 3 X EUDC
- Cold soak
- Cold start NEDC test
- Hot start NEDC test
- ARTEMIS Urban test
- ARTEMIS Road test
- ARTEMIS Motorway test
- Steady state tests : 120 km/h, 90 km/h, 50 km/h
- End of test

The test programme was constructed using the principles of statistical experimental design. Each fuel was tested three times in each vehicle, with typical test orders for diesel and gasoline vehicles being:

Diesel

Test Block 1	DC → DB → DA
Test Block 2	DB → DA → DC
Test Block 3	DA → DC → DB

Gasoline

Test Block 1	GB → GA
Test Block 2	GA → GB
Test Block 3	GA → GB

Each fuel was tested once in each block of tests, minimising the risk of fuel comparisons being contaminated by any drift in vehicle performance or other time-related effects. The test order also minimised the number of pairs of back-to-back tests on the same fuel to ensure that the results were truly independent.

In the event, a number of tests were identified as invalid by the test laboratory and these were repeated, but not always immediately. In some instances, certain cycles within a test were deemed to be invalid while others were not; only the invalid cycles were repeated and again not always immediately. This meant that the final test order deviated from that originally planned and the test orders varied from cycle to cycle.

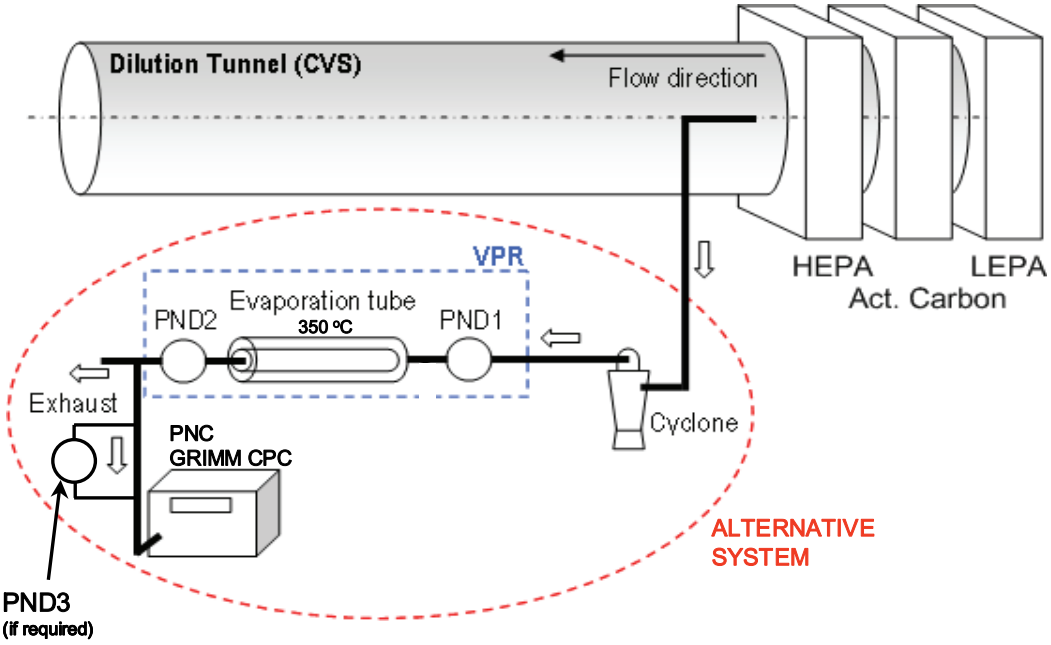
Sulphur Purging and Trap Conditioning Procedures

The last test of each day was at 120 km/h steady state conditions. At this condition, all vehicles were operated for approximately 15 minutes to stabilise the particle number emissions, followed by 10 minutes of test measurement.

Because the PMP methodology recommends conditioning the vehicle for 30 minutes at a 120 km/h steady state condition, it was not considered necessary to repeat this conditioning following the last test of each day. After the last test of each day, the vehicles were then preconditioned for the following day with 3 x EUDC or 1 x NEDC.

4.2. PARTICULATE CHARACTERISATION

Figure 1 Schematic of the Alternative Particle Measurement System Used in the Current Study



4.2.1. Comparison of the Alternative Particle Measurement System and the "Golden" Particle Measurement System Used in PMP

The Alternative Particle Measurement System used in this study has many features in common with the "golden" measurement system used in PMP. These include a sampling probe, a pre-classifier cyclone, heated dilution, volatile particle remover, cooling dilution, and a particle number counter system.

One key difference between these two systems is the type of cyclone pre-classifier that is located downstream of the air filters[5] and dilution tunnel (CVS).

- In the "golden" measurement system, particles are sampled by means of a Matter Engineering AG rotating disk diluter and a thermo-conditioning unit. After the particles are sampled, they are then measured by means of two modified TSI 3010 Condensation Particle Counters (CPC) at sampling points after the primary dilution and at the final sampling point.

[5] The air filtration system in front of the dilution tunnel consists of three different filters: LEPA (Low Efficiency Particulate Air), activated carbon, and HEPA (High Efficiency Particulate Air).

- In the Alternative System shown in **Figure 1** and used in the current study, particles are sampled by means of a Dekati Fine Particle Sampler (FPS) and measured only at the final sampling point using a Grimm Condensation Particle Counter (CPC Model 5.404).

At the start of the PMP programme, several different particle measurement systems were evaluated against the "golden" measurement system. The Alternative Particle Measurement System used in this study was one of the recognized alternatives to the "golden" measurement system and was shown to correlate well with actual measurements from the "golden" system.

At the end of the PMP programme, however, tighter criteria were established for all systems that could in future be described as "PMP compliant" and, against these new criteria, the alternative system used in this study did not fully comply. The tighter criteria related especially to the solid particle penetration efficiency of the Volatile Particle Remover (VPR).

For the purposes of the current comparative study, the Alternative Particle Measurement System is considered to be sufficiently similar to PMP compliant systems so that it can be used to compare results to the previous DG TREN study and infer the performance of vehicles and fuels against the Euro 5b PN emissions threshold.

4.2.2. Detailed Description of the Alternative Particle Measurement System

The Alternative Particle Measurement System had the following characteristics:

Efficient Dilution Air Filtration

- A standard full-flow CVS equipped with highly efficient dilution air filters for particles and hydrocarbons that reduces particle contributions from the dilution air to essentially zero.

Particle Size Pre-classification

- A sampling probe and URG cyclone pre-classifier which help to protect the downstream system components from particulate contamination and also set a nominal upper limit of 2.5 µm for the measured particle size.

Hot Dilution

- A first particle number diluter (PND1) which heats the sample aerosol to 250°C while simultaneously reducing the particle concentration in dilution air. This is done in order to evaporate volatile material that may be adsorbed on the carbonaceous particles and then prevent recondensation of this volatile material by reducing the partial pressure at the diluter exit.

Evaporation and Cold Dilution

- A low particle loss externally heated Evaporation Tube (ET) in which the aerosol sample is heated to 350°C and held for ~3 seconds while any additional semi-volatile material is evaporated. Any particles that remain in the aerosol after this point are considered to be "solid" or carbonaceous particles. This definition of "solid" particles is complementary to the definition of regulatory gaseous hydrocarbons: defined as those materials that are measured by a Flame Ionisation Detector (FID) downstream of a filter heated to 192°C.

- Immediately after the particles leave the ET, the particles enter a second particle number diluter (PND2), where they are cooled by further dilution. In this stage, the partial pressure of the gas phase is further reduced to prevent recondensation. The concentrations of particles are controlled such that they are below 10^4 cm^{-3} and thermophoretic losses are minimised.

Particle Number Counting

- A Grimm 5.404 Condensation Particle Counter with a strictly controlled counting efficiency curve receives the particle sample as it leaves PND2. This sets a nominal lower limit of ~21nm to the size range of particles measured. The strictly controlled counting efficiency curve is considered necessary to exclude the possible confounding of measurement data by low volatility hydrocarbons. These could appear as nucleation mode particles less than about 20 nm while including the primary carbon sphere size of about 20 nm.

4.3. COMPARISON OF MEASUREMENTS BETWEEN DG TREN AND PMP

The particle measurement system used in the DG TREN programme was not based on a legislated test procedure (i.e. using a dilution tunnel) for particle characterisation but employed a novel sampling system. Following dilution (via a porous tube diluter), the exhaust stream was split with one portion passing through a TD (to produce “dry” particles) while the other portion (“wet” particles) was characterised using a range of different analytical approaches. A full schematic of the measurement system has been presented previously [9].

The “dry” particles were measured using an Electrical Low Pressure Impactor (ELPI) and the total particle count reported as a summation of the counts over Stages 1-7 (i.e., by omitting the filter stage). This technique gave a total count for all particles with electrical mobility diameters between 30 and 1000 nm.

In the PMP measurement system, the exhaust stream (from the dilution tunnel) is subjected to a secondary hot dilution, which prevents recondensation of any volatile material that may be adsorbed to the carbonaceous particles. The resultant stream of “dry” carbonaceous particles is measured using a Condensation Particle Counter (CPC) which does not discriminate based on particle size and measures (as described above) all particles having electrical mobility diameters greater than 23 nm.

5. STATISTICAL ANALYSIS METHODOLOGY

The statistical methods used to analyse the data from this study are similar to those used in the DG TREN programme [9,15].

Each emission measurement (particulate mass, particle number, HC, CO, NO_x, CO_2) was examined on a vehicle-by-vehicle and cycle-by-cycle basis (cold and hot NEDC, ARTEMIS Urban, Road, and Motorway cycles, and steady state conditions at 50, 90, and 120 km/h).

In the EPEFE gasoline project [16] and other similar studies [9,15,17-21], the variability in emission and particulate measurements has typically been found to follow a lognormal distribution, with the degree of scatter increasing as the emission level increases. Plots of standard deviation vs. mean suggest that particulate mass and particle number measurements also behaved in this way in the current study (see **Appendix 4**). This assumption is harder to rigorously verify for some of the gaseous emissions where the levels of emissions differ little from fuel to fuel in any particular vehicle. Nevertheless, all subsequent statistical analyses are based on the assumption of lognormality as the physical mechanisms suggest that this is the most plausible model for emissions data.

The data were examined for outliers by inspecting studentized residuals (residuals divided by their standard errors). Only two gaseous emission values were rejected (see **Appendix 5** for details). A number of zero results (for example, CO emissions from diesel cars at 50 km/h) were queried, but most were retained as it was deemed that emissions were in fact below the detection limit.

Significant time trends (at $P < 5\%$[6]) were found in 28 of the 192 data sets (4 vehicles × 6 emissions × 8 cycles). These data could be adjusted to what they might have been had all the tests been conducted at the midpoint of the test programme. Trend correction generally has little effect on mean emissions for those cars and cycles where the test order was well randomised. Nevertheless, trend correction does reduce standard errors and error bars and helps to discriminate between fuels. Trend correction has more influence in data sets where the repetition of invalid tests rendered the test order non-random (e.g. particulate mass measurements over the cold NEDC in Vehicle E). For this reason, six data sets were corrected where the trend was significant at $P < 1\%$ and corrections were made on either the natural scale or the log scale to best reflect the patterns in the data.

The average gaseous emissions (HC, CO, NO_x, CO_2) and PM emissions for each vehicle and cycle are given in **Appendices 2** and **3**.

Consistent with previous studies [9,15,17,20,21], arithmetic means have been used in this report to summarize PM and gaseous emission measurements, in spite of the lognormality of the data. This is because logarithmic (i.e. geometric) means underestimate total emissions to the atmosphere. On the other hand, geometric means were used to average particle number measurements. This is because total particle numbers can differ by one or more orders of magnitude, an effect that can unduly inflate arithmetic means. For this reason, geometric means have been used to ensure that the means of particle number results are not dominated by one or two very high results.

[6] $P < 5\%$ = the probability, P, that such an event could be observed by chance when no real effect exists is less than 5%. In other words, we are 95% confident that the effect is real.

In the various plots in subsequent sections, gaseous emissions and particulate mass emissions are plotted on the original g/km scale. Standard errors and error bars are computed using weighted analysis of variance techniques (see **Appendix 5**). Logarithmic axes are used when plotting particle number measurements.

In the bar charts presented in **Section 6**, the error bars show the mean value ± 1.4 x standard error of mean.

The factor 1.4 in this equation was selected purely for consistency with EPEFE [16] and with recent CONCAWE reports [9,15,17,20,21]. Emissions from two fuels will not be significantly different from one another at P < 5% unless there is a sizeable gap between their error bars[7]. See **Appendix 5** for further discussion.

[7] The original rationale was that when two fuels were significantly different from one another at P < 5%, their error bars would not overlap. However error bars based on a factor 1.4 are too narrow for determining significant differences in the DG TREN and PMP programmes where fewer tests were carried out.

6. TEST RESULTS AND DISCUSSION

The average gaseous emissions (HC, CO, NO_x, CO_2), PM, and PN emissions for each vehicle and cycle are given in **Appendices 2** and **3**.

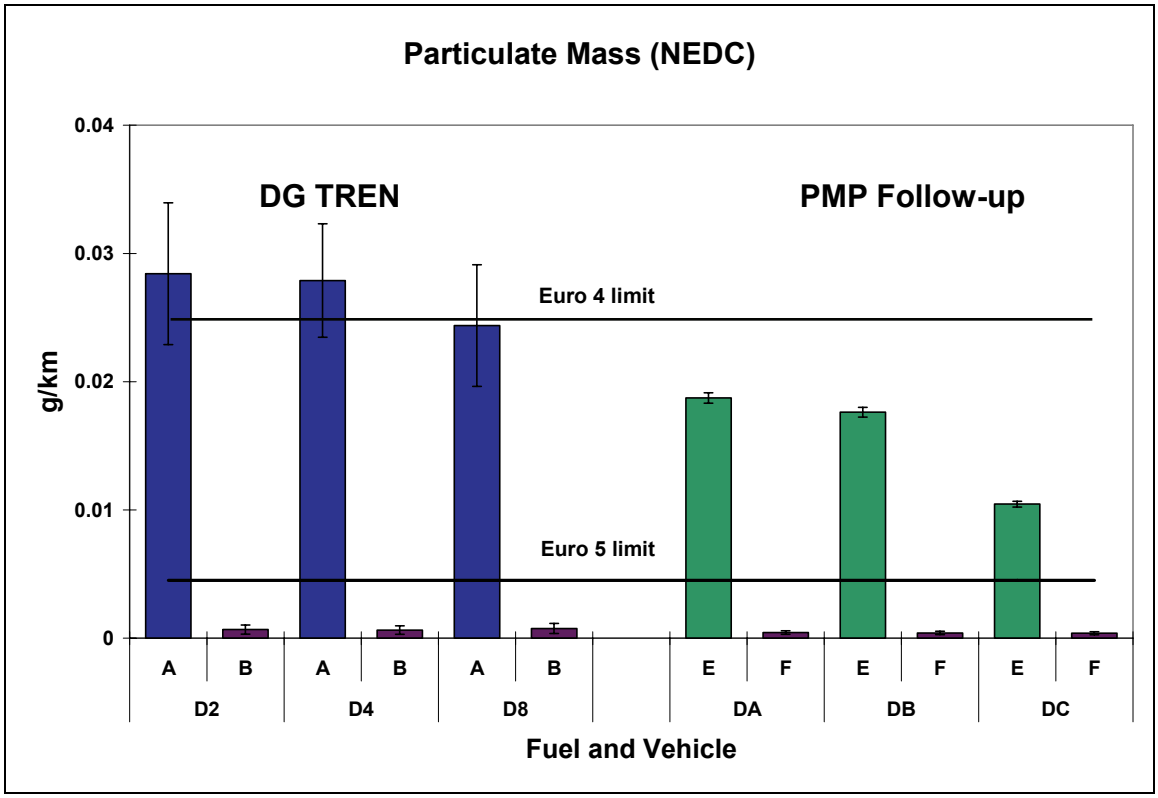
6.1. DIESEL VEHICLES

6.1.1. Particulate Mass Emissions

Transient Tests

Both light-duty diesel vehicles in the current study were certified to Euro-3 emission limits. **Figure 2** shows the PM emissions over the NEDC, while **Figure 3** shows PM emissions over the Artemis Motorway cycle. This Artemis cycle is shown because it is most unlike the NEDC with respect to speed (and therefore temperature) and thus the most likely cycle to show extremes in PM results.

Figure 2 Comparison of PM Emissions (Arithmetic Means) from Diesel Vehicles over the NEDC from the DG TREN Study and from the Current PMP Follow-up Study



As shown in **Figure 2**, both Vehicles E and F in the current study generated PM emissions well below the Euro 4 limits. In addition, the DPF-equipped vehicle (Vehicle F) produced PM emissions well below the Euro 5 limit on all fuels and at least an order of magnitude lower than those for the non-DPF-equipped vehicle (Vehicle E).

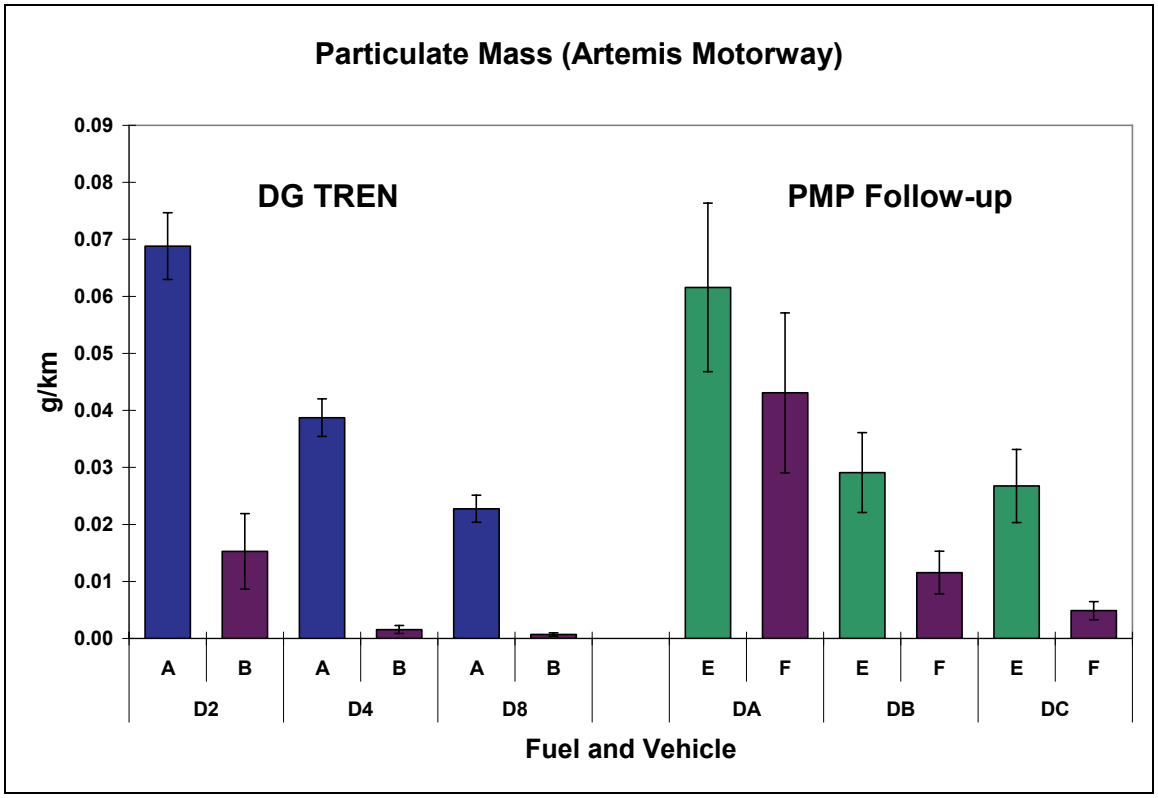
Although both Vehicles A and E were certified to Euro-3 emissions levels, Vehicle A (2002 Model Year) from the DG TREN study generated higher PM emissions than did Vehicle E (2004 Model Year) on all three test fuels.

The PM emissions from the DPF-equipped vehicle (Vehicle B/F) were very low in both studies. Although the PM emissions on comparable fuels appeared to be somewhat higher in the DG TREN study compared to the current study, the difference was not statistically significant.

The impact of fuel sulphur on PM emissions is slight as demonstrated by comparing fuels that differ in sulphur content by almost 300 mg/kg (Fuels D2 and D4 in the DG TREN study and Fuels DA and DB in the current study). This effect was observed in Vehicle E and, to a lesser extent, in Vehicle A but there was no impact of sulphur found in Vehicle B/F. Comparing the results obtained on different fuels, the FT fuel (Fuel D8 and DC) produced lower PM emissions than the other two fuels.

Compared to the NEDC results, the PM emissions were much higher in the Artemis Motorway cycle for all vehicles (**Figure 3**). In addition, the PM emissions from Vehicle E were similar to the PM emissions from Vehicle A on comparable fuels even though Vehicle E represents more advanced technology.

Figure 3 Comparison of PM Emissions (Arithmetic Means) from Diesel Vehicles over the Artemis Motorway Cycle from the DG TREN Study and from the Current PMP Follow-up Study



The impact of fuel sulphur on PM was much larger over the Artemis Motorway cycle compared to the NEDC. As seen by comparing **Figures 2** and **3**, consistent differences between the PM emissions for Fuels DA and DB and for Fuels D2 and

D4 are most likely due to increased sulphate formation over the higher temperature Artemis Motorway cycle.

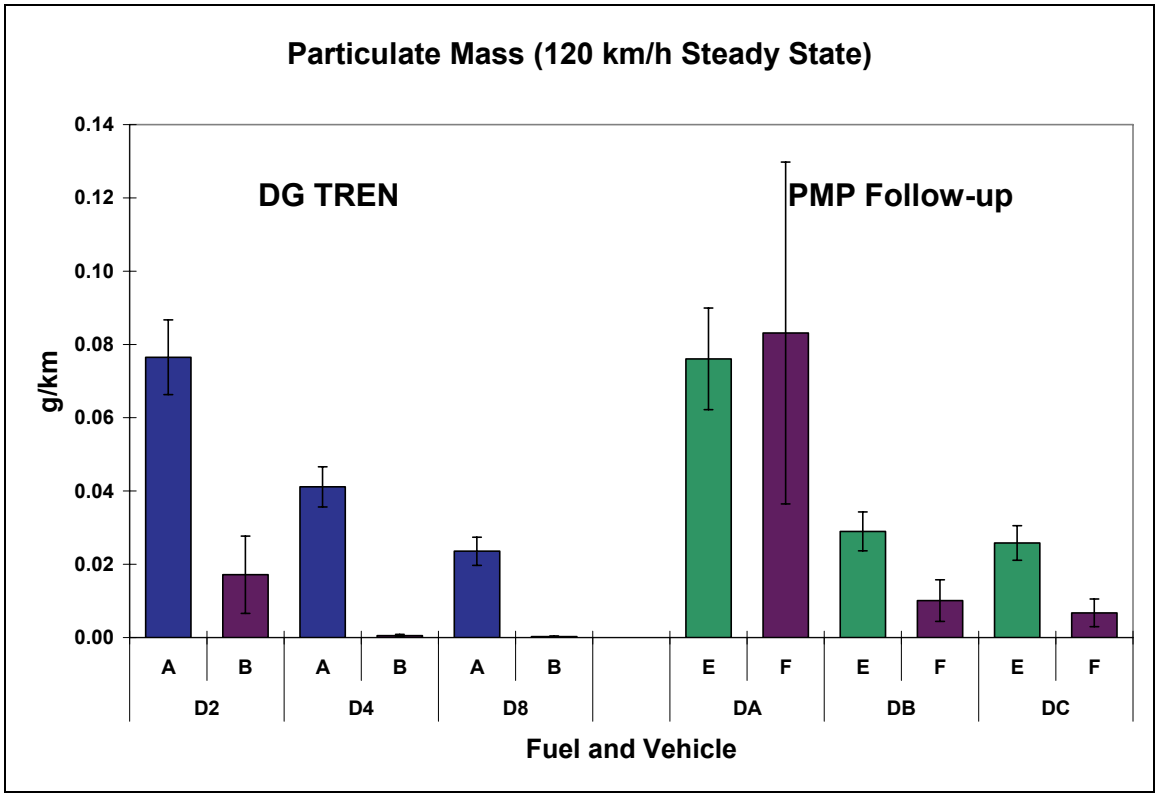
The PM emissions from Vehicle F were considerably higher on comparable fuels in the current study compared to the earlier DG TREN study (for example, compare Vehicle F tested on Fuel DA with Vehicle B tested on Fuel D2). This again may be due to differences in the vehicle's age, mileage, or condition at the time of testing or to the state of DPF regeneration at the time the measurements were made. In both studies, the Fischer-Tropsch fuel (Fuels D8 and DC) gave the lowest PM emissions over the Artemis Motorway cycle.

Steady state Tests

Three steady-state tests at 50, 90, and 120 km/h were also evaluated. Trends in PM emissions with fuel type were related to the steady-state speed, that is, higher speed (and temperature) conditions produced very similar trends to those observed in the Artemis Motorway cycle. At lower speeds (and temperatures), PM emissions were more in line with those observed over the NEDC.

As an example, **Figure 4** shows the PM emissions results for the 120 km/h steady-state test condition.

Figure 4 PM Emissions (Arithmetic Means) from Diesel Vehicles at the 120 km/h Steady State Condition from the DG TREN Study and from the Current PMP Follow-up Study



6.1.2. Particle Number Emissions

Transient Tests

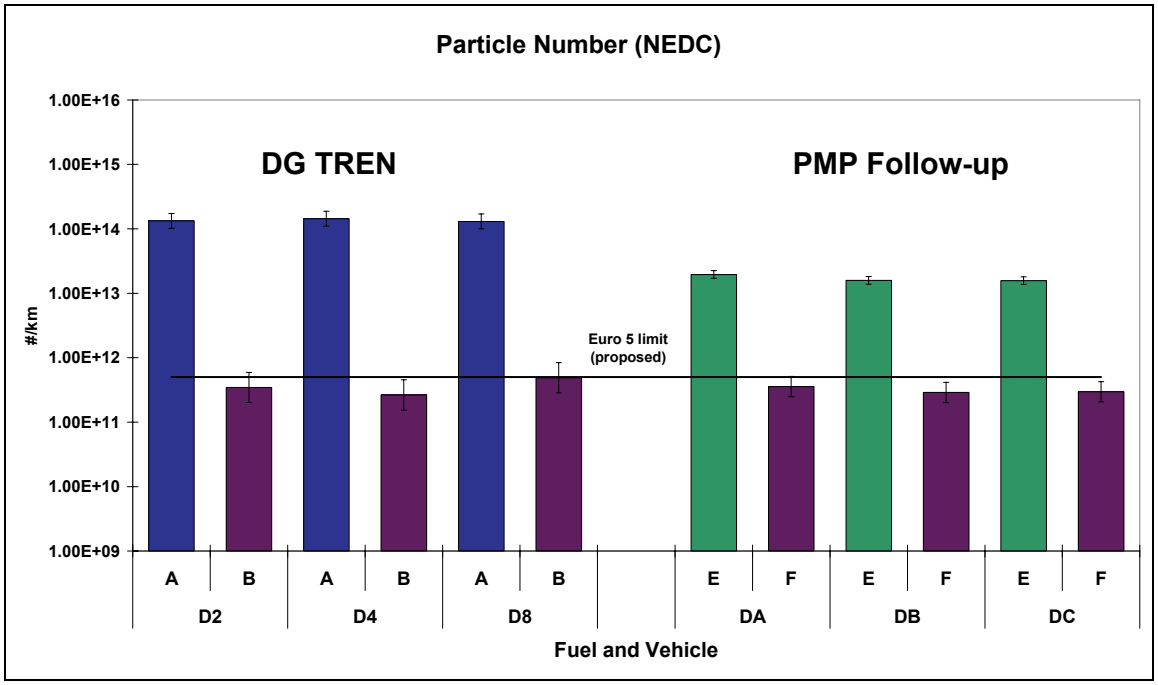
It might be expected that changes in PM emissions would also be reflected in changes in accumulation mode (carbonaceous) particles. In the DG TREN study, the PN measurement is given by the total count for ELPI Stages 1-7 (30 to 1000 nm particle diameters). That study included the use of a TD and represented a direct measure of carbonaceous particles.

In the current study, using the alternative particle measurement system based on the PMP programme, carbonaceous particles were measured (following hot dilution) with a Condensation Particle Counter (CPC). Because the measured particle numbers can vary over a wide range, PN emissions are typically shown on a logarithmic scale.

As seen in **Figure 5** and demonstrated by Vehicle B/F, the PN emissions over the NEDC were consistent between the DG TREN study and the current study, even though different measurement systems had been used. The newer technology Vehicle E showed about an order of magnitude lower PN emissions compared to Vehicle A, consistent with the PM results shown in **Figure 2**.

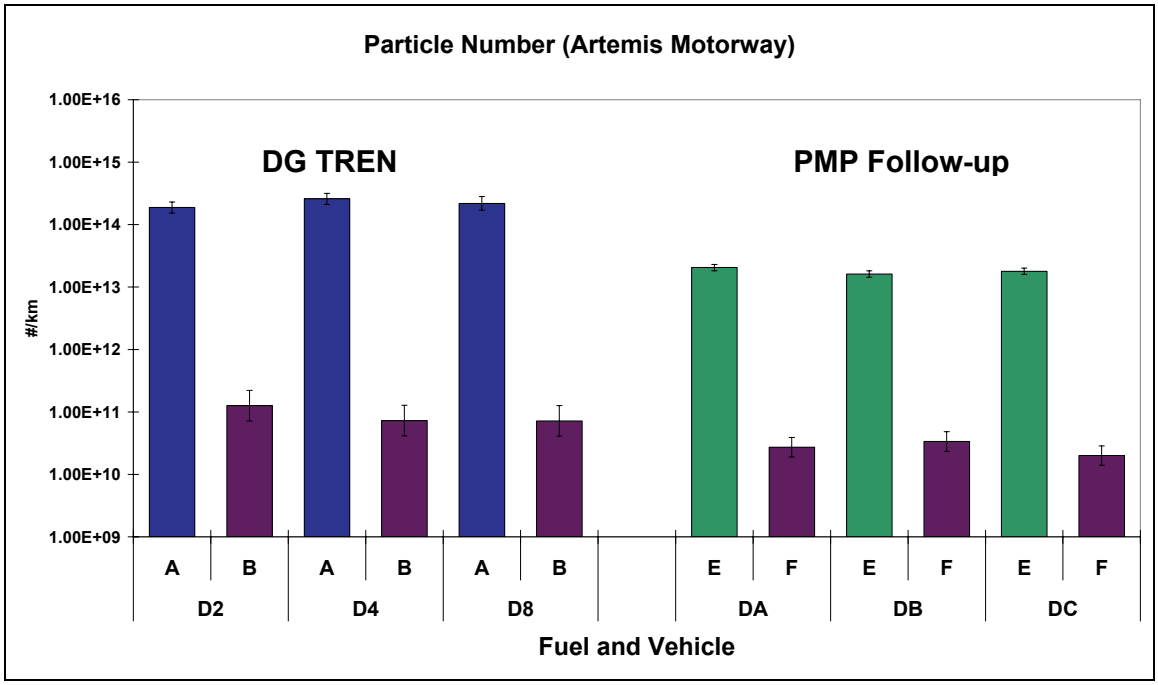
There were no apparent differences between fuels. The use of a Diesel Particulate Filter (in Vehicle B/F) reduced the carbonaceous PN by about two orders of magnitude compared to Vehicles A and E.

Figure 5 PN Emissions (Geometric Means) from Diesel Vehicles over the NEDC from the DG TREN Study and from the Current PMP Follow-up Study



The same observations applied to all other test conditions, whether transient or steady state. As an example, the PN emissions over the Artemis Motorway cycle are shown in **Figure 6**.

Figure 6 PN Emissions (Geometric Means) from Diesel Vehicles over the Artemis Motorway Cycle from the DG TREN Study and from the Current PMP Follow-up Study



The higher operating temperatures over the Artemis Motorway cycle made no apparent difference in the PN emissions on a per kilometre basis compared to the NEDC, even though the PM emissions increased considerably (**Figures 2** and **3**). This observation supports the previous conclusion that the increase in PM is most likely due to sulphate particles, which are removed by the hot dilution process before the carbonaceous particles are counted by the CPC.

Steady state Tests

Three steady-state tests at 50, 90, and 120 km/h were also evaluated and the results are summarized in **Appendices 2** and **4**. The PN emissions were very similar between the Artemis Motorway cycle and each of the steady-state conditions and there were no apparent trends in PN emissions with fuel type.

6.2. GASOLINE VEHICLES

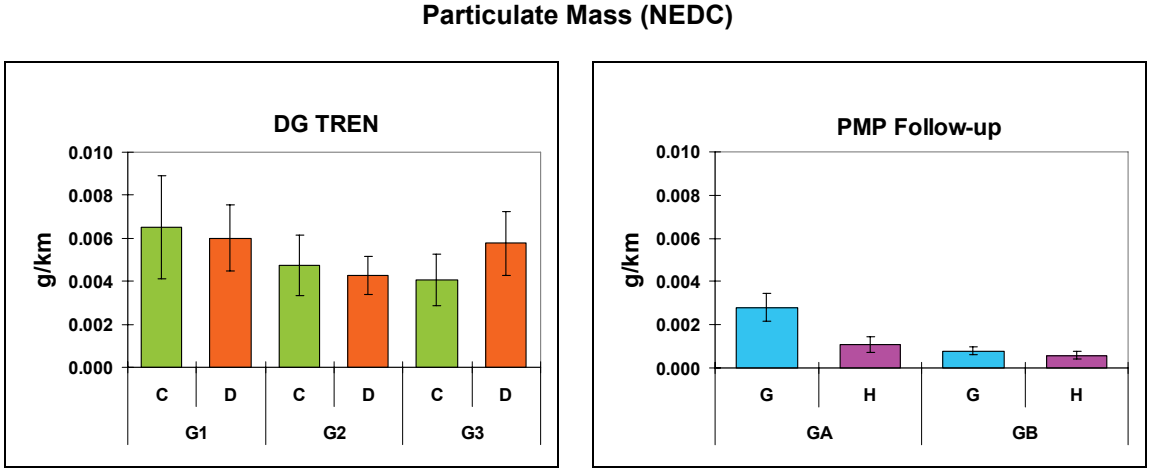
6.2.1. Particulate Mass Emissions

Transient Tests

Even though PM is not a regulated emission for gasoline vehicles, PM measurements were completed for the two GDI vehicles using the standard procedure. For consistency within this report, PM emissions results are again discussed first.

Figure 7 shows the PM emissions from the GDI vehicles over the NEDC.

Figure 7 PM Emissions (Arithmetic Means) from Gasoline Vehicles over the NEDC from the DG TREN Study and from the Current PMP Follow-up Study

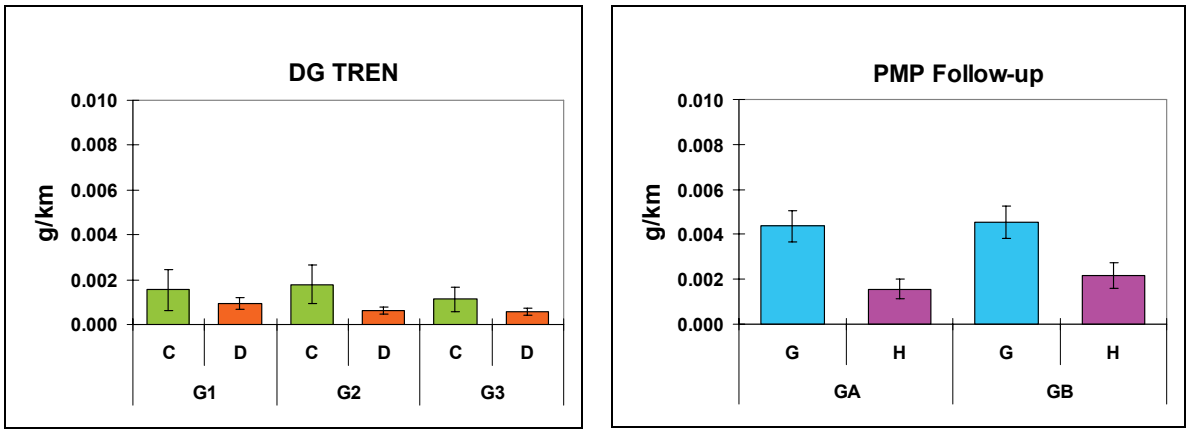


Comparing the DG TREN and PMP follow-up results, the GDI vehicles generated measurable amounts of PM emissions over the NEDC, much lower than for the conventional light-duty diesel vehicles but higher than the DPF-equipped light-duty diesel vehicle.

In the current study, the PM emissions from Vehicle G were higher than from Vehicle H and both vehicles produced lower PM emissions from Fuel GB compared to Fuel GA. Both Vehicles G and H gave lower PM emissions than for the two vehicles tested in the DG TREN study. This may be due to improvements in the GDI engines.

Figure 8 shows the PM emissions measured over the Artemis Motorway cycle.

Figure 8 PM Emissions (Arithmetic Means) from GDI Vehicles over the Artemis Motorway Cycle from the DG TREN Study and from the Current PMP Follow-up Study



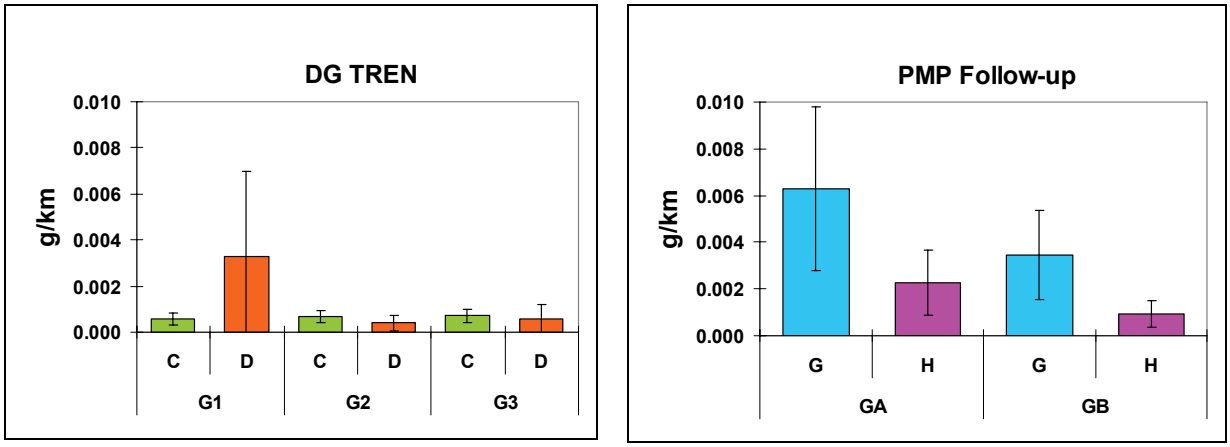
In the current study, the PM emissions over the Artemis Motorway cycle were measurably higher for Vehicle G compared to Vehicle H, which is presumably a consequence of different engine technology.

Steady state Tests

Steady-state tests were conducted at 50, 90, and 120 km/h and the results of these tests are summarized in **Appendix 4**. At the 120 km/h steady state test in the current study (**Figure 9)**, PM emissions were quite variable compared to the NEDC and Artemis Motorway cycles. More consistent trends were observed in the DG TREN study where higher PM emissions were seen over the Artemis Motorway cycle, with one exception (Fuel D in Vehicle G1). Similar trends were observed for tests run at 50 and 90 km/h steady-state conditions.

Figure 9 PM Emissions (Arithmetic Means) from GDI Vehicles at the 120 km/h Steady State Condition from the DG TREN Study and from the Current PMP Follow-up Study

Particulate Mass (120 km/h Steady State Condition)



6.2.2. Particle Number Emissions

Transient Tests

Figures 10 and **11** show the PN emissions from the GDI vehicles over the NEDC and Artemis Motorway cycles.

Figure 10 PN Emissions (Geometric Means) from GDI Vehicles over the NEDC from the DG TREN Study and from the Current PMP Follow-up Study

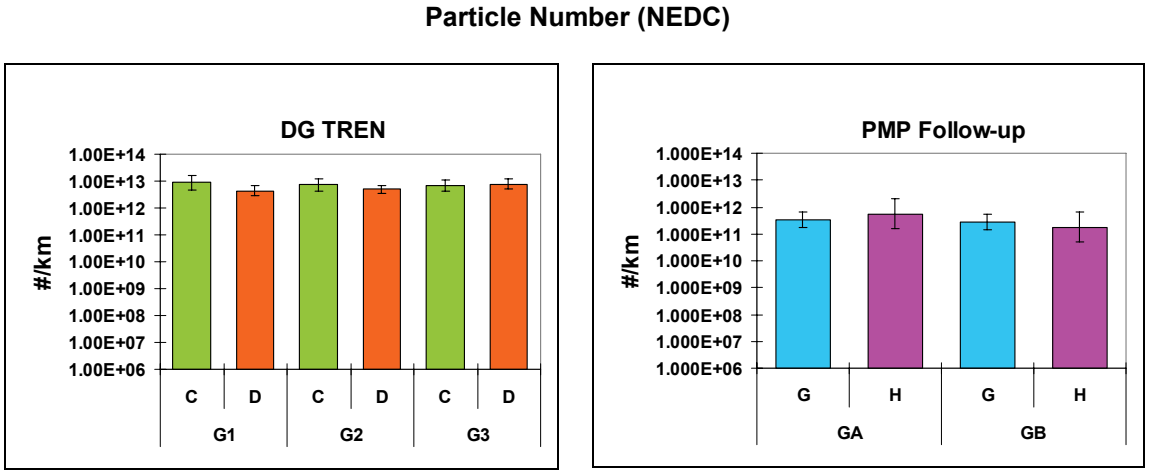
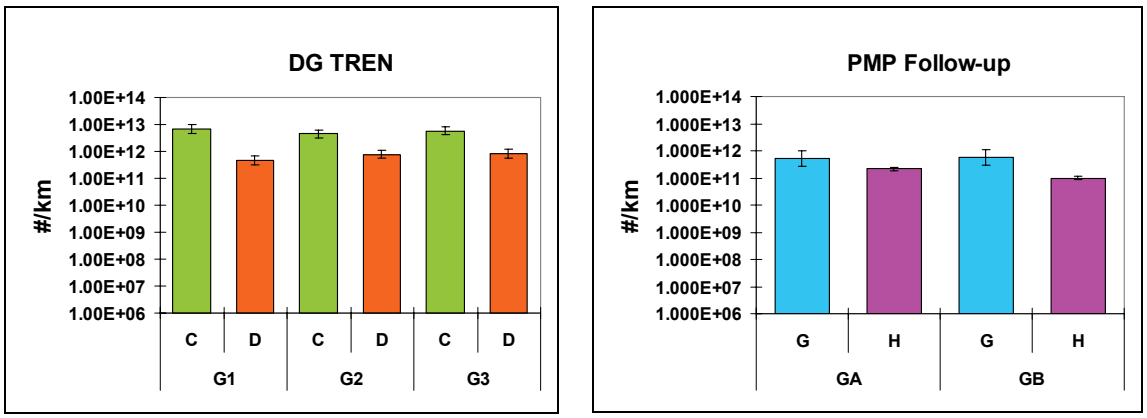


Figure 11 PN Emissions (Geometric Means) from GDI Vehicles over the Artemis Motorway Cycle from the DG TREN Study and from the Current PMP Follow-up Study



In the current study, both GDI vehicles emitted measurably lower PN emissions than similar vehicles tested in the DG TREN study for both the NEDC and Artemis Motorway cycle. This may indicate improvements in engine-out emissions control for the more advanced technology vehicles used in the current study. Absolute values in the PMP follow-up programme were consistent irrespective of driving cycle.

Steady-state Tests

Steady-state tests were also conducted at 50, 90, and 120 km/h and the results of these tests are summarized in **Appendix 4**. While there was little effect of steady state speed on PN emissions from the diesel vehicles, this was only true at 90 and 120 km/h for the GDI vehicles. At 50 km/h, the emissions were 1-2 orders of magnitude lower, though the reason for this difference is not understood.

6.3. PARTICULATE MASS AND PARTICLE NUMBER

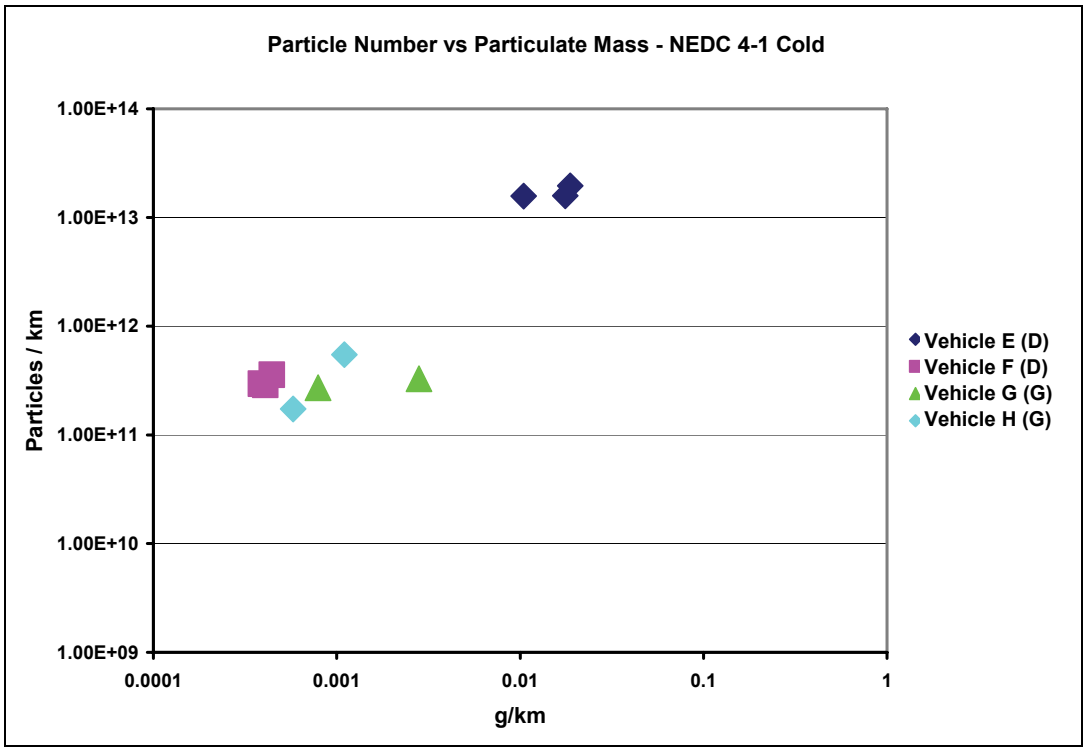
The introduction of a new PN emissions measurement along with the existing PM standard has raised the question as to the relevance of particle number and an appropriate level for vehicle compliance. The PMP protocol only measures carbonaceous particles and as such could merely be a surrogate for the PM measurement, which is dominated by accumulation mode (i.e. carbonaceous) particles. If this is the case, the PN measurement may not give any additional information on vehicle performance compared to the regulated PM measurement.

Work carried out during PMP [5] has indicated that at current emissions levels, the PN emissions measurement is a more repeatable and a more sensitive technique than that in use for PM determinations.

Within the current study, we have compared the PM and PN emissions for all vehicles and fuels over the range of driving cycles and conditions tested.

Figure 12 shows the correlation between PM and PN emissions for all vehicles and fuels over the cold NEDC. **Figure 13** shows the same correlation over the Artemis Motorway cycle. As with the regulated emissions, these two figures again demonstrate the extreme in observations, presumably as a direct result of the temperature differences in these test cycles. Values from steady state conditions generally fall between the value obtained over the NEDC and Artemis Motorway cycles.

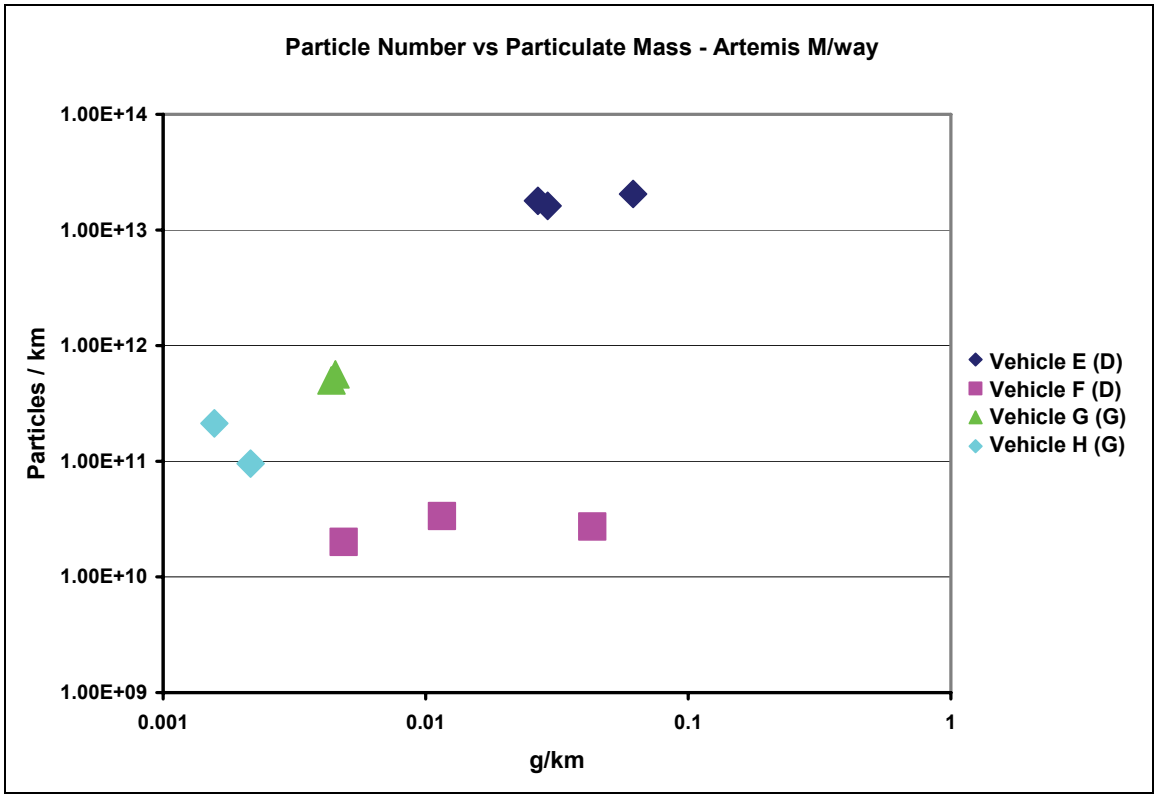
Figure 12 Correlation of PM and PN Emissions for All Vehicles and Fuels in the Current PMP Follow-up Study over the Cold NEDC



Note: In this figure, PM emissions (x-axis) represent arithmetic means while PN emissions (y-axis) represent geometric means.

Figure 12 shows that there is a broad correlation between the PM and PN emissions for all diesel and gasoline vehicles tested in the current study over the cold NEDC. For the two diesel vehicles, consistent values were measured over the range of fuels tested, although the DPF-equipped vehicle (Vehicle F) showed significantly lower values in both PM and PN emissions.

Figure 13 Correlation of PM and PN Emissions for All Vehicles and Fuels in the Current PMP Follow-up Study over the Artemis Motorway Cycle



Note: In this figure, PM emissions (x-axis) represent arithmetic means while PN emissions (y-axis) represent geometric means.

Figure 13 shows that at the higher speed and temperature Artemis Motorway cycle, Vehicle E is the highest emitter for both PM and PN emissions. While there is a small fuel effect observed on the PM measurement, there is little variation (or increase) on the emitted PN emissions. The DPF-equipped vehicle (Vehicle F), however, shows a significant increase in PM emissions (compared to the PM emissions in the NEDC) with a marked fuel effect while also showing lower particle numbers by about three orders of magnitude.

The observed fuel effects on PM emissions are probably due to increased sulphate formation at the higher operating (and catalyst) temperatures of the Artemis Motorway cycle. The PN emissions do not include the sulphate contributions because they contribute mostly to the nucleation mode and are therefore not counted in the accumulation mode (carbonaceous) particle number.

The behaviour of the diesel vehicles over the different cycles indicates that there are differences to be observed in emissions characteristics depending on the test cycle

employed. The measurement of PN appears to produce additional information beyond that given by the regulated PM measurement alone.

The gasoline vehicles did not appear to be as sensitive to cycle effects as the diesel vehicles although the PM results from the gasoline vehicles were less reproducible.

6.4. REGULATED GASEOUS EMISSIONS

The regulated gaseous emissions were analysed for this test programme with the full results reported in **Appendices 2** and **3.** A brief summary of the main conclusions are summarized below.

6.4.1. Regulated Gaseous Emissions from Diesel Vehicles

Gaseous emissions data from the diesel Vehicles E and F are included in **Appendix 2**.

- HC Emissions:
  - The FT diesel fuel (Fuel DC) gave substantially lower HC emissions than did Fuels DA and DB in both diesel vehicles (Vehicles E and F) over all test cycles.
  - The high sulphur fuel (Fuel DA) produced slightly higher HC emissions than the low sulphur fuel (Fuel DB) over most of the test cycles in both vehicles. However, these differences were not considered significant.
  - Over the cold NEDC, the HC emissions from Fuels DA and DB were particularly high in Vehicle E. Similar trends were seen for the steady state tests, where the HC emissions were lower, with Fuel DA producing significantly more HC emissions then Fuel DB in Vehicle E.
- CO Emissions:
  - The CO emissions from both Fuels DA and DB were particularly high in both vehicles over the cold NEDC. The CO emissions for these fuels were also very much higher than for the FT fuel (Fuel DC) which gave very low CO emissions in all cycles in both Vehicles E and F.
  - Fuels DA and DB gave moderate CO emissions over the Artemis Road and Motorway cycles and the steady state tests but with few consistent trends.
- NOx Emissions:
  - The NOx emissions were much higher than the HC and CO emissions over all the Artemis and steady state cycles for both vehicles and all fuels.
  - The differences in NOx emissions among the three diesel fuels over all test cycles and steady state speeds were generally small with few consistent trends.
- CO_2 Emissions:
  - The CO_2 emissions were lower for the FT fuel (Fuel DC) than for Fuels DA and DB over all test cycles, including the NEDC, Artemis, and steady state speeds, for both vehicles.

- No discernible differences were seen between Fuels DA and DB over all the test cycles.

6.4.2. Regulated Gaseous Emissions from Gasoline Vehicles

Gaseous emissions data from the GDI Vehicles G and H are included in **Appendix 3**.

- HC Emissions:
  - The HC emissions for both GDI vehicles (Vehicles G and H) were generally low over all test cycles except for the cold NEDC.
  - Fuel effects on the HC emissions were small and not significant for any of the tests.
- CO Emissions:
  - The CO emissions from Vehicle G were much higher than from Vehicle H over all test cycles and steady state speeds, with the highest levels found over the Artemis Motorway cycle.
  - Differences between fuels were small and seldom significant.
- NOx Emissions:
  - The NOx emissions were much lower for the GDI vehicles than for the diesel vehicles. However, the fuel effects were small and again not significant for both vehicles over all test cycles and steady state speeds.
- CO_2 Emissions:
  - Fuel GA frequently gave higher CO_2 emissions than Fuel GB over all test cycles and steady state speeds for both vehicles. This effect was often statistically significant.

7. CONCLUSIONS

7.1. GENERAL CONCLUSIONS

- The measurement techniques for carbonaceous PN emissions used in the DG TREN programme (using and ELPI) and this PMP follow-up study (using a CPC) gave comparable results on similar vehicles and fuels, despite different exhaust dilution and sampling protocols.
- Measurements of both PM and PN emissions were broadly consistent between this study and the DG TREN “Particulates” programme carried out in 2001.
- The more advanced technology vehicles (both diesel and gasoline) tested in this PMP follow-up study gave lower PM and PN emissions over the NEDC compared to the previous DG TREN study.
- A broad correlation was found between PM and PN emissions for all vehicles (diesel and gasoline) over the NEDC.
- Over the higher temperature Artemis Motorway cycle, there was less of a correlation between PM and PN emissions where an increased production of volatile particles is included in the mass but not in the number measurements.
- The PN emissions from GDI cars were about the same order of magnitude as from the DPF-equipped diesel vehicles.
- At all steady state test conditions, the diesel vehicles gave similar PN emissions to those measured over the Artemis Motorway cycle. However, at 50 km/h both GDI vehicles produced lower PN emissions (by 1-2 orders of magnitude) than over the Artemis Motorway cycle.

7.2. DIESEL VEHICLES

- Regulated emission tests showed that PM emissions are reduced in the DPF-equipped vehicles to levels that are well below the Euro 5 limit.
- For the non-DPF equipped vehicles, both the DG TREN and PMP follow-up studies showed that there is no significant impact of fuel sulphur on PM emissions over the NEDC. The FT fuel produced lower PM emissions in the non-DPF equipped vehicle in both studies.
- Over the higher temperature Artemis Motorway cycle, the impact of fuel sulphur on PM emissions was more significant, most likely due to higher sulphate formation at the higher temperature test conditions. This is not reflected in the PN emissions measurements in either study, where the methodology was designed to eliminate volatile material (including sulphate) from the carbonaceous particles.
- In the steady state tests, the PM emissions appeared to be related to the speed (and temperature) of the test. This was highlighted by the similar PM results obtained between the Artemis Motorway and the 120 km/h steady state test.
- Although the PN measurement methods from the DG TREN programme and the PMP follow-up study used different principles, the carbonaceous particle results were comparable for similar vehicles, fuels, and driving cycles.
- Measurement of PN emissions on the same DPF-equipped vehicle gave consistent results between both studies over both the NEDC and Artemis Motorway cycle.

- Over the NEDC, the DPF-equipped vehicles produced PN emissions that were about two orders of magnitude lower than in the non-DPF equipped vehicles and lower than the threshold that has been set for Euro 5 emissions limits.
- The PN emissions in both studies showed no apparent impact from fuel composition with different test cycles on the same vehicle.
- The NEDC and Artemis Motorway cycle gave the same PN emissions on non-DPF equipped vehicles on comparable fuels. For the DPF-equipped vehicle, slightly lower PN emissions were observed in the Artemis Motorway cycle compared to the NEDC. The PN emissions over all steady state test conditions were similar to those measured over the Artemis Motorway cycle.

7.3. GASOLINE VEHICLES

- The GDI vehicles emit lower PM emissions over the NEDC in the current study compared to the DG TREN study. This is thought to be related to improvements in GDI technology.
- The only observed fuel effect on PM emissions was for Vehicle G over the NEDC. No other significant fuel effects were observed on the PM emissions.
- Over the NEDC, both GDI vehicles had higher PM emissions than did the DPF-equipped diesel vehicle. The reverse was true over the Artemis Motorway cycle where PM emissions from the GDI vehicles were up to an order of magnitude lower than from the DPF-equipped diesel vehicle.
- Consistent with the DG TREN study, there was little impact of fuel composition and vehicles on PN emissions over the NEDC and Artemis Motorway cycle. Vehicle H showed a small sensitivity to fuel composition over the Artemis Motorway cycle.
- PN emissions from the GDI vehicles were of the same order as the DPF-equipped vehicles over both the NEDC and Artemis Motorway cycle.
- At the 50 km/h test condition, the GDI vehicles produced 1-2 orders of magnitude lower PN emissions compared with other steady state conditions and the Artemis Motorway cycle.

8. GLOSSARY

ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems
CADC	Common Artemis Driving Cycle
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPC	Condensation Particle Counter
CVS	Constant Volume Sampling System
DG TREN	Directorate General for Transport and Energy (European Commission)
DI	Direct Injection
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
ELPI	Electrical Low Pressure Impactor
EN 228	CEN Specification for European Unleaded Petrol
EN 590	CEN Specification for European Diesel Fuel
EPEFE	European Programme on Emissions, Fuels and Engine Technologies
ESC	European Stationary Cycle
ET	Evaporation Tube
EUDC	Extra Urban Driving Cycle
FID	Flame Ionization Detector
FIE	Fuel Injection Equipment
FT	Fischer-Tropsch
FPS	Fine Particle Sampler
GDI	Gasoline Direct Injection
GRPE	Working Party on Pollution and Energy (UNECE)
GTL	Gas to Liquids
HC	Hydrocarbon emissions

HD	Heavy-duty
HEPA	High Efficiency Particulate Air filter
KV40	Kinematic Viscosity at 40°C
LD	Light-duty
LEPA	Low Efficiency Particulate Air
NEDC	New European Driving Cycle
NOx	Nitrogen Oxides
PM	Particulate Matter or Mass
PMP	Particle Measurement Programme
PN	Particle Number
PNC	Particle Number Counter
PND	Particle Number Diluter
Significant	Statistically significant at >95% confidence
TC	Turbo Charged
TD	Thermal Denuder
T10	Temperature (°C) at which 10% v/v diesel is recovered
T50	Temperature (°C) at which 50% v/v diesel is recovered
T95	Temperature (°C) at which 95% v/v diesel is recovered
UNECE	United Nations Economic Commission for Europe
URG	URG Corporation 116 S. Merritt Mill Road, Chapel Hill, NC 27516 USA E-mail: info@urgcorp.com
VPR	Volatile Particle Remover

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- Mr. Peter Zemroch, for statistical analysis and experimental design support.

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APPENDIX 1 FUEL ANALYSES FROM DG TREN STUDY

Extracted from CONCAWE Report 1/05 (2005) titled:

Fuel Effects on the Characteristics of Particle Emissions from Advanced Engines and Vehicles

1. TEST FUELS

The core test fuels were selected based on the objectives to develop representative emissions factors for current and future vehicle fleets as well as to enhance understanding of fuel effects. Existing knowledge indicated fuel sulphur as a key fuel effect on particle emissions, both in terms of enabling new exhaust after-treatment technology and as a direct effect on sulphate emissions.

In view of the importance of fuel sulphur in enabling advanced exhaust after-treatment systems, the recent update to the EU Fuels Directive requires 50 mg/kg max sulphur content in both gasoline and diesel fuels from 2005, with “appropriate geographic availability” of sulphur-free fuels (10 mg/kg max sulphur content) from the same date, progressing to 100% coverage of sulphur free fuels by 2009 (this date being subject to a further review for diesel). No other fuel property changes are required for 2005, except for the already agreed reduction in gasoline aromatics to 35% v/v max.

1.1 Diesel Fuels

Test fuels D2 to D4 were designed to study the sulphur effect, using a base fuel with sulphur content as low as possible and with other properties held as close as possible to average year 2000/05 levels. Sulphur levels were adjusted by doping the base fuel (D4) with di-(tertiary butyl)-di-sulphide, to cover the range from current sulphur levels to the projected sulphur-free case. The target levels for the other fuel properties were derived from work on the reference fuel specifications for 2005 and beyond.

Additional fuels were included to assess the largest possible range of fuel properties. These included two additional sulphur-free fuels with extremely low density and aromatics content: Swedish Class 1 diesel fuel and Fischer-Tropsch diesel fuel. A 5% RME blend, produced from fuel D4, was also tested. A second diesel fuel at the current sulphur level (year 2000) but with higher density and aromatics content was also included in the test matrix.

Table 4 summarizes the analytical data for these test fuels.

Table 4 Diesel Fuel Analyses

Fuel Code			**D2 to D4**	**D8**
Fuel Description	**Units**	**Test Method**	**Sulphur Matrix**	**Fischer Tropsch**
Cetane Number		D 613	**54.0**	**>75**
Cetane Index		IP 380	**51.1**	*
Density	kg/m^3	EN ISO 3675	**845**	**785**
T50	°C	EN ISO 3405	**282**	**298**
T95	°C	EN ISO 3405	**358**	**349**
FBP	°C	EN ISO 3405	**368**	**355**
CFPP	°C	EN 116	**-33**	**0**
KV @ 40°C	mm^2/s	EN ISO 3104	**3.04**	**3.61**
Poly-aromatics	% m/m	IP 391	**4.3**	**0.0**
Mono-aromatics	% m/m	IP 391	**14.1**	**0.1**
Carbon	% m/m		**86.8**	**85.0**
Hydrogen	% m/m		**13.2**	**15.0**
H:C ratio	Atomic ratio		**1.82 : 1**	**2.12: 1**
LHV	MJ/kg		**42.87**	**44.17**
Lubricity	µm	HFRR	**375**	**279**
FAME	% v/v		**Nil**	**Nil**
Sulphur	mg/kg	D 3120/2622		**<5****
Fuel D2	**EN 590: 2000**		**280**	
Fuel D3	**EN 590: 50 ppm S**		**38**	
Fuel D4	**EN 590: 10 ppm S**		**8**	

* Cetane index equation is not applicable to FT diesel fuel.
** Below detection limit

1.2 Gasoline Fuels

Again, the test fuels were mainly designed around the sulphur effect, using base fuels with other properties held as close as possible to average year 2000/05 levels, but with as low a sulphur content as possible. Sulphur levels were adjusted to typical current, 2005 and 2009 levels by doping with thiophene. The target levels for the base fuel properties were derived from work on the development of reference fuel specifications for 2005 and beyond, and should therefore provide a firm basis for the development of emissions factors. Analytical data are given in **Table 5**.

Table 5 Gasoline Analyses

Fuel Code			**G1**	**G2**	**G3**
Fuel Description	**Units**	**Test Method**	**EN 228: Year 2000**	**EN 228: 50 ppm S**	**EN 228: 10 ppm S**
Characteristic			**Result**	**Result**	**Result**
RON		ISO 25164	**96.4**	**96.8**	**96.8**
MON		ISO 25163	**85.3**	**86.0**	**86.0**
Density	kg/m^3	EN ISO 3675	**753**	**749**	**748**
DVPE	kPa	EN ISO 13016	**58.7**	**57.7**	**57.7**
E70	% v/v	EN ISO 3405	**29.4**	**32.5**	**32.5**
E100	% v/v	EN ISO 3405	**50**	**51.2**	**51.2**
E150	% v/v	EN ISO 3405	**85.5**	**86.1**	**86.1**
FBP	°C	EN ISO 3405	**195**	**193**	**193**
Residue	% v/v	EN ISO 3405	**1.0**	**1.1**	**1.1**
Olefins	% v/v	D 1319	**8.8**	**9.9**	**9.9**
Aromatics	% v/v	D 1319	**35.4**	**33.4**	**33.4**
Benzene	% v/v	EN 12177:98	**0.8**	**0.6**	**0.6**
Sulphur	mg/kg	D 3120/2622	**143**	**45**	**6**
Lead	mg/l	EN 237	**<1**	**<1**	**<1**
Phosphorus	mg/l		**<1**	**<1**	**<1**
Carbon	% m/m	D 5291	**86.3**	**86.0**	**86.0**
Hydrogen	% m/m	D 5291	**13.0**	**13.2**	**13.2**
Oxygen	% m/m		**0.7**	**0.8**	**0.8**

1.3 Lubricant Selection

A common batch of lubricant was used for the programme in order to minimise effects from differing lubricants. The lubricant was selected as being representative of current European lubricant quality, i.e. a conventional mineral oil formulation meeting: SAE 15W-40, ACEA Class A3 / B3 for light-duty, ACEA Class E3 for heavy-duty, with a sulphur content of 0.6% m/m. This oil was suitable for use in both gasoline and light-duty and heavy-duty diesel engines.

APPENDIX 2 EMISSIONS FROM DIESEL VEHICLES

The uncorrected and corrected mean emissions, including particles/km, from the diesel Vehicles E and F are summarized in this Appendix. See **Section 5** of the report for details on uncorrected versus corrected results.

Particulate Mass (g/km) - Arithmetic means

Vehicle	Fuel	NEDC 4-1 Cold		NEDC 4-1 Hot		Artemis Road	Artemis Urban	Artemis M/way	Steady State 50 km/h	Steady State 90 km/h	Steady State 120 km/h
		Uncorr	Corr	Uncorr	Corr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr
E	DB	0.0169	0.0176	0.0171	0.0171	0.0151	0.0263	0.0291	0.0090	0.0167	0.0290
E	DA	0.0181	0.0187	0.0189	0.0188	0.0197	0.0235	0.0616	0.0114	0.0305	0.0761
E	DC	0.0113	0.0105	0.0111	0.0112	0.0123	0.0181	0.0268	0.0068	0.0149	0.0258
F	DB	0.0004		0.0003		0.0006	0.0017	0.0115	0.0009	0.0006	0.0101
F	DA	0.0004		0.0008		0.0011	0.0014	0.0431	0.0006	0.0023	0.0831
F	DC	0.0004		0.0004		0.0005	0.0013	0.0049	0.0007	0.0007	0.0067

Particles/km - Geometric means

Vehicle	Fuel	NEDC 4-1 Cold	NEDC 4-1 Hot	Artemis Road	Artemis Urban	Artemis Motorway	Steady State 50 km/h	Steady State 90 km/h	Steady State 120 km/h
		Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr
E	DB	1.588E+13	1.745E+13	1.700E+13	2.262E+13	1.615E+13	8.503E+12	2.655E+13	2.446E+13
E	DA	1.958E+13	1.852E+13	1.544E+13	2.518E+13	2.052E+13	1.074E+13	2.987E+13	2.975E+13
E	DC	1.571E+13	1.599E+13	1.858E+13	2.099E+13	1.791E+13	9.702E+12	2.829E+13	2.517E+13
F	DB	2.887E+11	1.785E+10	3.541E+10	3.628E+10	3.364E+10	1.352E+10	1.014E+10	2.819E+10
F	DA	3.568E+11	3.413E+10	4.352E+10	2.971E+10	2.728E+10	1.211E+10	8.059E+09	4.823E+10
F	DC	2.962E+11	4.172E+10	5.379E+10	3.435E+10	2.005E+10	1.482E+10	1.025E+10	3.675E+10

HC (g/km) - Arithmetic means

Car	Fuel	NEDC 4-1 Cold	NEDC 4-1 Hot	Artemis Road	Artemis Urban	Artemis Motorway	Steady State 50 km/h	Steady State 90 km/h	Steady State 120 km/h
		Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr
E	DB	0.1058	0.0209	0.0204	0.0255	0.0121	0.0063	0.0142	0.0088
E	DA	0.1006	0.0267	0.0221	0.0304	0.0140	0.0091	0.0182	0.0118
E	DC	0.0160	0.0096	0.0120	0.0124	0.0087	0.0058	0.0103	0.0071
F	DB	0.0219	0.0090	0.0108	0.0243	0.0025	0.0044	0.0085	0.0006
F	DA	0.0241	0.0102	0.0120	0.0261	0.0027	0.0047	0.0077	0.0012
F	DC	0.0105	0.0052	0.0058	0.0127	0.0015	0.0051	0.0048	0.0002

CO (g/km) - Arithmetic means

Car	Fuel	NEDC 4-1 Cold	NEDC 4-1 Hot	Artemis Road	Artemis Urban	Artemis Motorway		Steady State 50 km/h	Steady State 90 km/h	Steady State 120 km/h
		Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Corr	Uncorr	Uncorr	Uncorr
E	DB	0.4599	0.0240	0.0080	0.0605	0.0093		0.0000	0.0057	0.0077
E	DA	0.4561	0.0442	0.0103	0.0616	0.0093		0.0006	0.0076	0.0085
E	DC	0.0390	0.0043	0.0055	0.0074	0.0077		0.0000	0.0055	0.0068
F	DB	0.2079	0.0365	0.0093	0.0394	0.0242	0.0263	0.0000	0.0056	0.0134
F	DA	0.2286	0.0336	0.0127	0.0283	0.0241	0.0221	0.0000	0.0080	0.0113
F	DC	0.0369	0.0022	0.0048	0.0023	0.0217	0.0209	0.0000	0.0047	0.0109

NOx (g/km) - Arithmetic means

Car	Fuel	NEDC 4-1 Cold	NEDC 4-1 Hot	Artemis Road	Artemis Urban	Artemis Motorway	Steady State 50 km/h	Steady State 90 km/h	Steady State 120 km/h	
		Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Corr
E	DB	0.333	0.368	0.571	0.837	0.787	0.134	0.247	0.510	0.513
E	DA	0.309	0.355	0.537	0.801	0.759	0.124	0.248	0.516	0.519
E	DC	0.353	0.370	0.532	0.850	0.736	0.155	0.240	0.478	0.472
F	DB	0.468	0.427	0.730	1.069	1.312	0.093	0.503	0.580	
F	DA	0.458	0.446	0.745	1.099	1.361	0.103	0.465	0.526	
F	DC	0.415	0.390	0.642	0.975	1.213	0.100	0.484	0.493	

CO_2 (g/km) - Arithmetic means

Car	Fuel	NEDC 4-1 Cold	NEDC 4-1 Hot	Artemis Road	Artemis Urban	Artemis Motorway	Steady State 50 km/h	Steady State 90 km/h	Steady State 120 km/h	
		Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Corr
E	DB	162.99	152.07	148.70	229.36	190.46	84.08	144.35	183.61	183.87
E	DA	163.36	152.15	148.23	223.29	190.24	84.03	143.25	183.07	183.46
E	DC	158.07	147.22	142.84	214.72	183.02	83.61	139.82	176.35	175.72
F	DB	179.09	167.70	167.86	268.44	209.58	91.12	152.44	205.77	
F	DA	178.31	167.71	168.69	270.91	211.33	93.68	155.47	204.92	
F	DC	168.83	158.58	159.60	257.37	201.26	87.82	144.62	197.97	

APPENDIX 3 EMISSIONS FROM GASOLINE VEHICLES

The uncorrected and corrected mean emissions, including particles/km, from the gasoline Vehicles G and H are summarized in this Appendix. See **Section 5** of the report for details on uncorrected versus corrected results.

Particulate Mass (g/km) - Arithmetic means

Car	Fuel	NEDC 4-1 Cold	NEDC 4-1 Hot	Artemis Road	Artemis Urban	Artemis M/way	Steady State 50 km/h		Steady State 90 km/h	Steady State 120 km/h
		Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Corr	Uncorr	Uncorr
G	GA	0.0028	0.0004	0.0007	0.0014	0.0044	0.0003		0.0005	0.0063
G	GB	0.0008	0.0003	0.0007	0.0010	0.0045	0.0007		0.0006	0.0034
H	GA	0.0011	0.0008	0.0007	0.0027	0.0016	0.0009	0.0009	0.0003	0.0023
H	GB	0.0006	0.0003	0.0006	0.0008	0.0022	0.0004	0.0003	0.0003	0.0009

Particles/km - Geometric means

Car	Fuel	NEDC 4-1 Cold	NEDC 4-1 Hot	Artemis Road	Artemis Urban	Artemis Motorway	Steady State 50 km/h	Steady State 90 km/h	Steady State 120 km/h
		Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr
G	GA	3.291E+11	4.595E+10	1.786E+11	2.267E+11	5.009E+11	3.796E+08	2.194E+11	4.958E+10
G	GB	2.723E+11	5.801E+10	2.510E+11	7.293E+10	5.665E+11	3.161E+08	3.835E+11	6.268E+11
H	GA	5.481E+11	3.291E+11	3.030E+11	8.314E+11	2.132E+11	8.614E+09	2.535E+10	8.103E+10
H	GB	1.732E+11	6.685E+10	2.684E+11	5.520E+11	9.550E+10	1.973E+09	1.615E+10	6.327E+10

HC (g/km) - Arithmetic means

Car	Fuel	NEDC 4-1 Cold	NEDC 4-1 Hot	Artemis Road	Artemis Urban	Artemis Motorway	Steady State 50 km/h	Steady State 90 km/h	Steady State 120 km/h
		Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr
G	GA	0.0867	0.0196	0.0044	0.0093	0.0119	0.0029	0.0033	0.0017
G	GB	0.0796	0.0248	0.0033	0.0103	0.0114	0.0022	0.0037	0.0017
H	GA	0.0422	0.0340	0.0125	0.0334	0.0078	0.0125	0.0012	0.0098
H	GB	0.0391	0.0403	0.0121	0.0514	0.0037	0.0075	0.0011	0.0061

CO (g/km) - Arithmetic means

Car	Fuel	NEDC 4-1 Cold	NEDC 4-1 Hot	Artemis Road	Artemis Urban	Artemis Motorway	Steady State 50 km/h	Steady State 90 km/h	Steady State 120 km/h
		Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr
G	GA	1.5250	0.8518	1.3970	0.8426	10.0953	0.1167	0.3442	0.1559
G	GB	1.6774	0.9087	1.2118	0.9863	9.7186	0.0869	0.3613	0.1884
H	GA	0.1623	0.1123	0.2001	0.2130	0.2167	0.0161	0.0097	0.0740
H	GB	0.2418	0.0740	0.1779	0.2147	0.1785	0.0079	0.0092	0.0538

NOx (g/km) - Arithmetic means

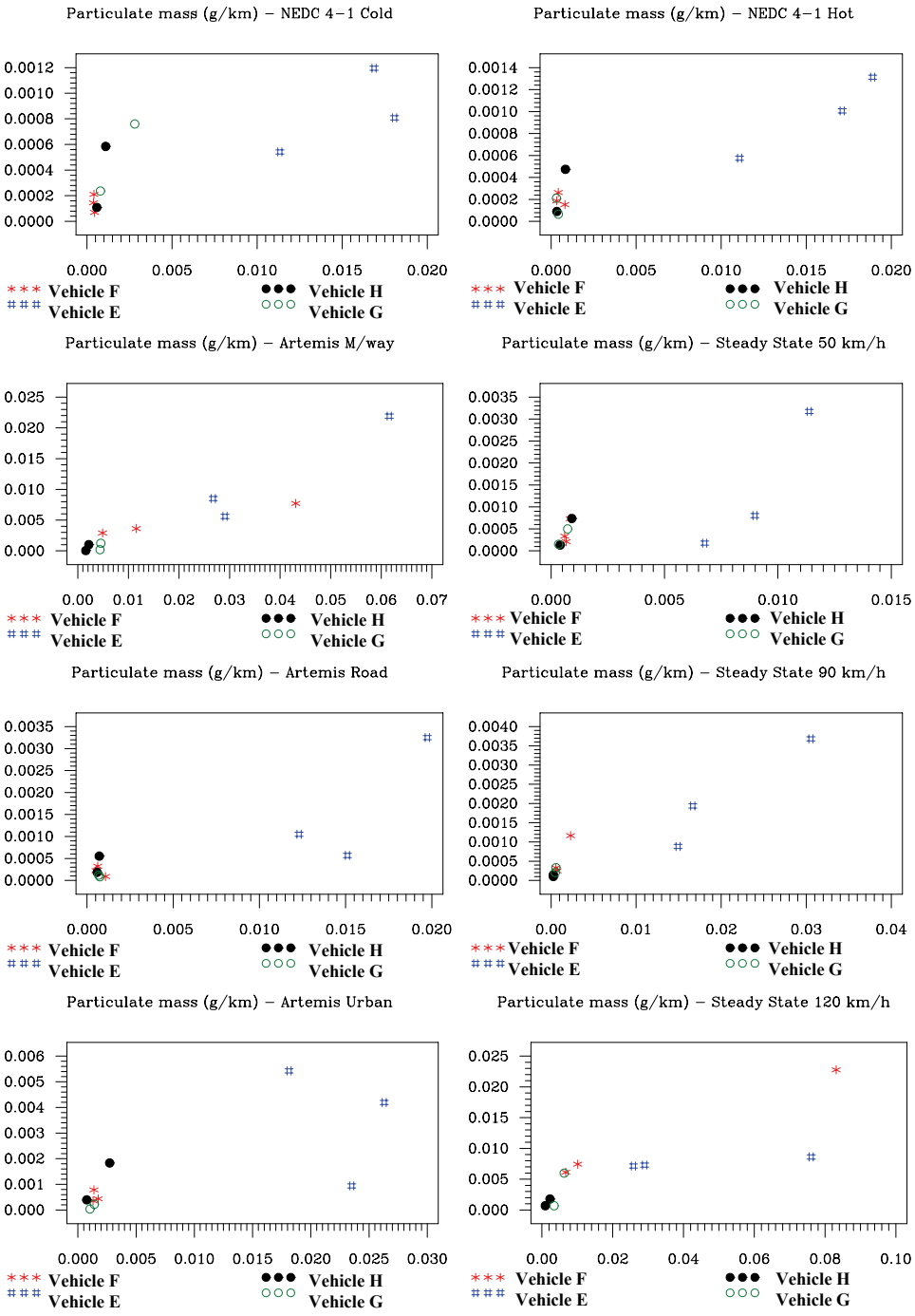
Car	Fuel	NEDC 4-1 Cold	NEDC 4-1 Hot	Artemis Road	Artemis Urban	Artemis Motorway	Steady State 50 km/h	Steady State 90 km/h	Steady State 120 km/h
		Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr
G	GA	0.045	0.046	0.078	0.146	0.300	0.094	0.030	0.465
G	GB	0.043	0.040	0.081	0.157	0.265	0.091	0.022	0.384
H	GA	0.030	0.042	0.101	0.235	0.023	0.003	0.001	0.017
H	GB	0.040	0.037	0.115	0.208	0.018	0.000	0.000	0.013

CO_2 (g/km) - Arithmetic means

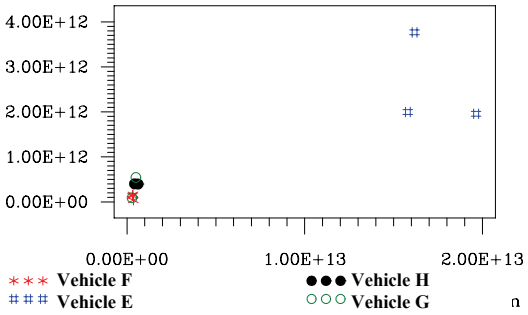
Car	Fuel	NEDC 4-1 Cold	NEDC 4-1 Hot	Artemis Road	Artemis Urban	Artemis Motorway	Steady State 50 km/h	Steady State 90 km/h	Steady State 120 km/h
		Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr	Uncorr
G	GA	203.67	189.58	189.47	290.66	230.29	122.73	178.79	232.61
G	GB	197.63	185.48	186.86	280.47	224.96	119.58	174.37	226.67
H	GA	170.46	157.09	150.03	247.87	212.30	104.41	150.63	203.83
H	GB	169.15	158.48	148.45	239.32	207.95	100.62	148.50	199.20

APPENDIX 4 PM AND PN: MEAN AND STANDARD DEVIATION

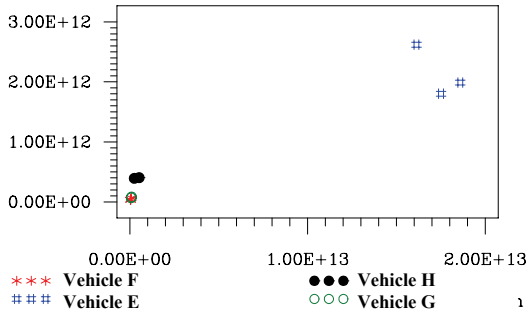
Each point in these figures depicts the mean and standard deviation of the repeat tests (usually 3) on a particular fuel in a particular vehicle.



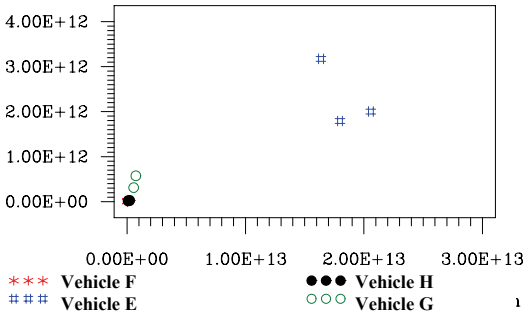
Particulate number (#/km) – NEDC 4-1 Cold



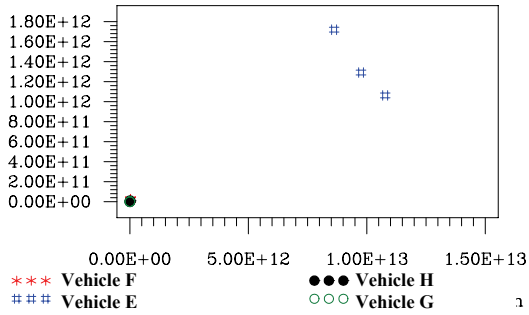
Particulate number (#/km) – NEDC 4-1 Hot



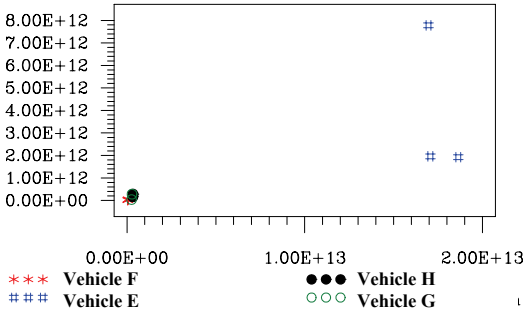
Particulate number (#/km) – Artemis M/way



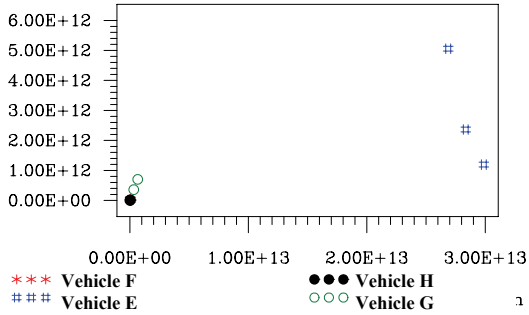
Particulate number (#/km) – Steady State 50 km/h



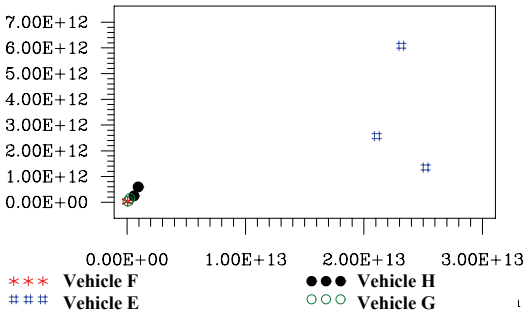
Particulate number (#/km) – Artemis Road



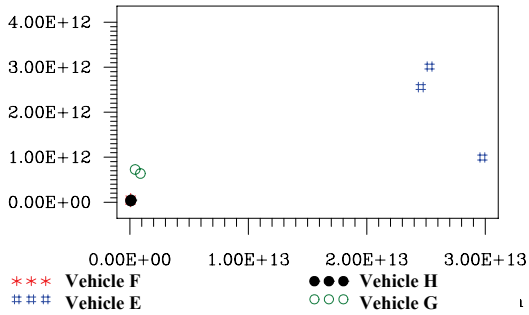
Particulate number (#/km) – Steady State 90 km/h



Particulate number (#/km) – Artemis Urban



Particulate number (#/km) – Steady State 120 km/h



APPENDIX 5 STATISTICAL DATA ANALYSIS

This appendix provides additional information on the statistical analysis methods discussed in **Section 5**.

Outlier detection using studentized residuals

The data were examined for possible outliers and trends by examining studentized residuals (residuals divided by their standard errors) in analysis of (co)variance models fitted to the measured emissions for a particular vehicle and cycle on a log-transformed scale. In this study, we fitted a one-way ANOVA model to each vehicle × cycle × emission combination with ln(emission) as the response variable and fuel as the classifying factor. Trends were sought by treating test order as a covariate, noting that test order varied not only from vehicle to vehicle but also from cycle to cycle within a vehicle. The studentized residuals were compared against the upper 5% and 1% points tabulated in [22].

Outliers are harder to detect using studentized residuals in small or noisy data sets than in large or self-consistent ones. Fearing that some potentially discordant points might be missed by analyzing the data one car at a time, we also pooled the data and fitted a two-way ANOVA model in car and fuel (without interaction) to log(emission). As variability levels often vary from vehicle to vehicle however, even on a log scale, pooling the data violates the assumptions underpinning such analyses. For that reason, the associated significance tests in the two-way ANOVA were regarded as indicative rather than definitive. Suspicious results were queried with the originating laboratory and were not rejected unless there were sound engineering reasons to believe that something untoward had happened in that particular test.

Only two results were rejected:

- Vehicle E - Artemis Motorway - Fuel DC:

  HC emissions = 0.000 g/km - analyzers started giving negative values and may have been incorrectly calibrated

- Vehicle H - Steady state 90 km/h - Fuel GB:

  CO_2 emissions (g/km) = 125.8 g/km - statistical outlier: value was much lower than other results in that vehicle

Arithmetic and geometric means and error bars

In **Appendices 2** and **3** and in the bar charts in **Section 6**, arithmetic means are used for gaseous emissions and particulate mass while geometric (i.e. logarithmic) means are used for particle number. Geometric means give excellent comparisons between fuels on a percentage basis but have the disadvantage of underestimating total emissions to the atmosphere. Arithmetic means give better estimates of total emissions to the atmosphere but can be inflated unduly by isolated high results.

Each vehicle × cycle × emission measurement data set was analysed separately. The standard errors of the arithmetic mean emissions for the various fuels were estimated from a weighted analysis of variance in which each emission measurement was assigned a weight equal to:

$$\text{weight} = 1 / (\text{mean emission for that fuel and vehicle})^2$$

to take account of the lognormality in the data (see [16], Annex 05).

In the bar charts presented in **Section 6**, the error bars show the mean value ± 1.4 x standard error of mean.

The factor 1.4 was chosen purely for consistency with EPEFE [16] and recent CONCAWE reports [6,7,9,15,17,20]. The original rationale was that, when two fuels were significantly different from one another at $P < 5\%$, their error bars would not overlap; this factor also gave 84% confidence that the true mean lay within the limits shown.

Error bars based on a factor 1.4 are too narrow for determining significant differences in the DG TREN and PMP programmes where fewer tests were carried out. Such an interpretation would require error bars based on factors in the region of 1.5 to 1.6 (DG TREN) and 1.7 to 1.8 (PMP) for diesel and 1.7 to 1.8 (DG TREN) and 2.0 (PMP) for gasoline, depending on the exact number of valid tests and whether or not a time correction has been applied.

APPENDIX 6 TEST PROGRAMME PROTOCOL

CONCAWE STF-25 Particle Measurement Programme

Measurement of Exhaust Particulate Emissions from Road Vehicles using "PMP" Test Method

1. Introduction

Shell Global Solutions has written this test protocol in preparation for the testing of four LD vehicles using the "PMP" testing method. This work will be carried out for CONCAWE FE/MG-STF/25.

2. Vehicle Selection & Preparation

General considerations:

New vehicles should be run-in for at least 8000 km. A similar conditioning period should be considered if the engine has been rebuilt (in order to allow deposits to build up to stabilised levels).

The last 500 km of the run-in should be used to condition the lubricant (same batch supplied for all vehicles by BP). This conditioning period is mandatory for the lubricant, so even if the vehicle has already run sufficient distance to be conditioned (e.g. 8000 km) a further 500 km is required after the lubricant has been changed.

The vehicle manufacturer's road-load model should be used if available, otherwise the road-load should be modelled using established laboratory procedures.

3. Fuel Selection, Storage and Handling

Drums should be stored in a cold area (below 5°C) for 12 hours prior to decanting fuel, to minimise vapour loss.

4. Test Order and Repeats

The daily protocol will be run in triplicate for each vehicle/fuel combination. Tests will be in single blocks with long repeats and the test fuel order should be randomised. A randomised test order is given below.

a. Diesel Vehicle

Block 1	Block 2	Block 3
D-C	D-B	D-A
D-B	D-A	D-C
D-A	D-C	D-B

b. Gasoline Vehicle

Block 1	Block 2	Block 3
G-B	G-A	G-A
G-A	G-B	G-B

5. Equipment & Measurements

a. Equipment

A description of the modified Particulate Mass (PM) and Particle Number (PN) measurement systems is taken from the Ricardo document for the “Inter-laboratory Correlation Exercise”, i.e. the PMP Light Duty round robin exercise.

From each test the following data should be collected:

- complete set of regulated emissions
- real-time total number of particles in exhaust aerosol using CPC

b. Test Conditions

This involves a daily protocol, with the following daily test sequence:

- Cold NEDC
- Hot NEDC
- Hot Artemis cycles (urban, road and motorway)
- Steady states at 50 km/h, 90 km/h and 120 km/h using road-load dynamometer settings

Test procedures to follow established practices for legislated emissions testing unless otherwise specified.

- Load road curve to be set a directed in Section 1.0.
- Test cell temperature to be set at 22°C (minimum 20°C).
- Vehicle cooling fan to follow vehicle road speed.

c. Bagging and Filter Paper Strategy

The bagging strategy and Filter Paper strategy will follow that of the PMP programme. The new PM sampling set-up does not use a back-up filter, i.e. the sample is not drawn through two filter papers mounted in series, but just a single paper (of modified medium). In addition to this, for the DPF vehicles, only a single filter paper is used for the whole test cycle, because of the low emissions level. The bagging strategy for the gaseous emissions remains as per the current regulations.

Cycle	Bagging Strategy	Filter Papers
NEDC (cold or hot)	Bag 1: 4 x ECE Bag 2: 1 x EUDC	DPF Diesel vehicle: Filter 1: Full Cycle Filter 2: not used Other Diesel vehicle: Filter 1: 4 x ECE Filter 2: 1 x EUDC Gasoline vehicle: Filter 1: 4 x ECE Filter 2: 1 x EUDC
Artemis cycles (road, urban or motorway). See note below.	Bag 1: Full Cycle Bag 2: not used	All vehicles: Filter 1: Full Cycle Filter 2: not used
Steady-State (50, 90 or 120 km/h)	Bag 1: Full Test Bag 2: not used	All vehicles: Filter 1: Full Test Filter 2: not used

Note: *For the Artemis cycles, the Full Cycle does not include all of the time that the test is run. In each cycle, Bag and Filter sampling starts part-way through the cycle – see Addendum 3. In the case of the Motorway cycle, the sampling ends before the end of the actual test.*

d. Daily Test Protocol and Conditioning Procedures

General comments:

- It is very important that the identical protocol is followed every day in order that the tests performed on different fuels or vehicles are truly comparable, and that the tests on the same fuels and vehicles are true repeats.
- A system of checks must be made on the vehicle and test facilities, as well as the instrumentation, to ensure consistent operation from day to day.
- For the vehicle, tyre pressures should be checked (3.5 bar recommended for chassis dynamometer operation), and regulated emissions monitored and checked for outliers.
- The coast down should be checked at intervals during the test programme.
- Scheduled maintenance on any of the test facilities should be avoided during any sequence of tests.

Specific test procedure:

- The following table lists the tests to be performed on each vehicle on a daily basis and the conditioning that is required for the test. After a test has been completed, it is preferable that the vehicle is stopped immediately and then restarted when the next conditioning phase is commenced rather than running at some arbitrary condition and duration before entering the next conditioning phase.

The precise daily schedule for measurement would therefore be:

No	Task	Vehicle Operation	Time (Est.)
1.0	Instrument warm-up and preparation	Engine off	30 mins.
1.1	Cold NEDC	Driving to cycle	20 mins.
1.2	Data storage, filter change and instrument preparation	Engine off	See note 2
2.0	Condition for hot-start	50 km/h	5 mins.
2.1	Prepare for NEDC	Engine off	5 mins.
2.2	Hot NEDC	Driving to cycle	20 mins.
2.3	Data storage, filter change and instrument preparation	Engine off	See note 2
3.0	Artemis Urban (includes non-sampled phase at start)	Driving to cycle	20 mins.
3.1	Data storage, filter change and instrument preparation	Engine off	See note 2
4.0	Artemis Road	Driving to cycle	20 mins.
4.1	Data storage, filter change and instrument preparation	Engine off	See note 2
5.0	Artemis Motorway (130 km/h)	Driving to cycle	20 mins.
5.1	Data storage, filter change and instrument preparation	Engine off	See note 2
6.0	120 km/h conditioning	120 km/h	5 mins.
6.1	120 km/h measurements	120 km/h	10 mins.
6.2	Data storage, filter change and instrument preparation	Engine off	See note 2
7.0	90 km/h conditioning	90 km/h high load	5 mins.
7.1	90 km/h measurements	90 km/h high load	10 mins.
7.2	Data storage, filter change and instrument preparation	Engine off	See note 2
8.0	50 km/h conditioning	50 km/h	5 mins.
8.1	50 km/h measurements	50 km/h	10 mins.
8.2	Data storage, filter change and instrument preparation	Engine off	See note 2

Notes:
(1) A conditioning phase is defined before the hot start NEDC (phase 2.0). This is not done for the three Artemis cycles as they all have a "Pre-Cycle" phase at the start, which is not included in the emissions data (see Addendum 3). The steady-state tests are preceded by 5 minutes conditioning prior to the 10 minute measurement phase, without any break in between.
(2) This time is not defined, and will be predominantly driven by the automated instrument calibration (emissions equipment) working in certification mode. It is important that a consistent time is taken at each stage, and this is repeated from day to day.

The above sequence is to be followed by the fuel change and conditioning phase, for which the precise daily schedule would therefore be:

No	Task	Details of Operation
9.0	Fuel change	Drain fuel and fill with 10 litres of new fuel. Idle engine for 5 minutes to flush system. Drain fuel again and fill with 25 litres of new fuel. If using external fuel tanks of smaller volume, then fill as achievable.
10.0	Specialist Sulphur purging or regeneration procedures.	Vehicle dependent – see Appendix 4.
11.0	Pre-conditioning for following day.	Vehicle dependent: Gasoline: 1 x ECE + 2 x EUDC Diesel: 3 x EUDC
12.0	Cold soak.	10 – 16 hours at 22°C

e. Notes:

If there is an extended break during the testing (e.g. lunch break or other), a warm-up procedure should be used, prior to continuing the test sequence. If the next test cycle is a transient cycle (i.e. phases 2 to 5), then a transient warm-up and conditioning should be used. If the next test cycle is a steady-state, then an extended steady-state warm-up and conditioning should be used. Proposed conditioning:

Following Cycle Type	Conditioning to be used
Transient test	1 x EUDC
Steady-state test	Additional 10 minutes running at the steady-state condition which is about to be tested (i.e. 50, 90 or 120 km/h as appropriate).

All instrument and PC clocks are to be synchronised to the nearest second, and checked on a daily basis, to facilitate time alignment of logged data.

Addendum 1 to TEST PROGRAMME PROTOCOL (Appendix 6)

Measurement Equipment for Particulate Mass and Particle Number

The following paragraphs are taken from the Ricardo document defining the LD round robin undertaken by the PMP. The description of the particle number measurement system (Section A1.2) is specific to the Golden System, but systems of similar technical specification are permitted.

A1.1 MEASUREMENT AND SAMPLING SYSTEMS FOR PARTICULATE MASS

A1.1.1 Introduction

The mass of particulate material emitted by each engine technology and for the combined phases of the NEDC test will be measured using the system defined below.

A1.1.2 Primary Dilution System

A full flow CVS exhaust dilution tunnel system meeting the requirements of Regulation 83 shall be used. The flow rate of dilute exhaust gas through the tunnel shall be 12m3/min at standard reference conditions (20°C and 1bar).

It is recommended that the dilution air used for the primary dilution of the exhaust in the CVS tunnel shall be first charcoal scrubbed and then passed through a secondary filter. The secondary filter should be capable of reducing particles in the most penetrating particle size of the filter material by at least 99.95%, or through a filter of at least class H13 of EN 1822; this represents the specification of High Efficiency Particulate Air (HEPA) filters.

If both gasoline and diesel vehicles are to be tested, then there shall be a dedicated dilution tunnel for each fuel type. If a single tunnel only is available, then priority should be placed on testing the golden vehicle and other diesel vehicles.

A1.1.3 Particulate Mass Sampling

A sample probe shall be fitted in the dilution tunnel. It shall be installed near the tunnel centre-line, 10 - 20 tunnel diameters downstream of the gas inlet and have an internal diameter of at least 12 mm. The sample probe will be sharp-edged and open ended, facing directly into the direction of flow.

A cyclone or impactor based pre-classifier shall be employed.

A pump will draw a sample of dilute exhaust gas proportional to the total tunnel flow through the sample pre-classifier and filter holder.

The distance from the sampling tip to the filter mount shall be at least five probe diameters, but shall not exceed 1,020 mm.

A1.1.4 Sample Pre-classifier

In accordance with the recommendations of the draft Regulation 83 document, a cyclone or impactor pre-classifier shall be located upstream of the filter holder assembly. The pre-classifier 50% cut point particle diameter shall be between 2.5 µm and 10 µm at the volumetric flow rate selected for sampling particulate mass emissions. The pre-classifier shall allow at least 99% of the mass concentration of 1µm particles entering the pre-classifier to pass through the exit of the pre-classifier at the volumetric flow rate selected

for sampling particulate mass emissions. Evidence of compliant performance to this specification shall be presented (e.g. manufacturer's calibration certificate).

A1.1.5 Sampling Filters

A1.1.5.1 Filter holder assembly
The filter holder assembly shall be of a design that provides for a single filter only. The shape of the holder should be such that an even flow distribution of sample across the filter stain area is achieved.

In order to meet the requirement that a temperature of 47±5°C be maintained for a period of at least 0.2s within 2.5cm of the filter face, the filter holder and transfer tubing from the CVS tunnel will either need to be heated directly, or be mounted inside a temperature-controlled enclosure.

A1.1.5.2 Filter medium
Pallflex TX40 Fluorocarbon coated glass fibre filters shall be employed. All filters will be drawn from a single batch procured by the project-managing laboratory.

A1.1.5.3 Filter size and Stain Area
The filter diameter shall be 47mm and the stain area shall be at least 1075 mm^2.

A1.1.5.4 Filter face velocity/ volumetric sample flow rate (x cm/s, y litres/min)
Filter face velocity shall be in the range 50 cm/s to 80 cm/s, which corresponds to a flow rate range of 35 L/min to 51 L/min. Filter face velocity should be calculated at 47°C.

A1.1.5.5 Filter Preparation
The particulate sampling filters shall be conditioned (as regards temperature and humidity) in an open dish that has been protected against dust ingress for at least 2 and for not more than 80 hours before the test in an air-conditioned chamber. After this conditioning the uncontaminated filters will be weighed and stored until they are used. If the filters are not used within one hour of their removal from the weighing chamber they shall be re-weighed.

The one-hour limit may be replaced by an eight-hour limit if one or both of the following conditions are met:

- a stabilised filter is placed and kept in a sealed filter holder assembly with the ends plugged, or;
- a stabilised filter is placed in a sealed filter holder assembly which is then immediately placed in a sample line through which there is no flow.

A1.1.5.6 Sample Filter Weighing
Once loaded, the used particulate filter shall be taken to the weighing chamber within one hour following the analyses of the exhaust gases. The filter shall be conditioned for at least 2 hours and not more than 80 hours and then weighed.

A1.1.6 Measurement Equipment and Environment

A1.1.6.1 Microgram balance
The analytical balance used to determine filter weight must have a precision (standard deviation) of better than 2 µg for a clean filter; better than 0.25µg for a reference weight and a resolution or readability of 1µg or better. To eliminate the effects of static electricity: the balance should be grounded through placement upon an antistatic mat and

particulate filters should be neutralised prior to weighing; this can be achieved by a Polonium neutraliser or a device of similar effect.

A1.1.6.2 Weighing Chamber Parameters

The temperature of the chamber (or room) in which the particulate filters are conditioned and weighed must be maintained to within 295K ± 3 K (22°C ± 3°C) during all filter conditioning and weighing. The humidity must be maintained to a dew point of 282.5K ± 3 K (9.5°C ± 3°C) and a relative humidity of 45 % ± 8 %. The environmental conditions of the weighing room during the test programme shall be monitored and reported.

Limited deviations from weighing room temperature and humidity specifications will be allowed provided their total duration does not exceed 30 minutes in any one filter conditioning period. The weighing room should meet the required specifications prior to personal entrance into the weighing room. During the weighing operation no deviations from the specified conditions are permitted.

A1.1.7 Calibration Requirements:

A1.1.7.1 Microbalance Calibration

The microbalance shall be calibrated according to the manufacturer's specification within 3 months prior to the commencement of the test programme.

A1.1.7.2 Reference Filter Weighing

At least two unused reference filters must be weighed within 4 hours of, but preferably at the same time as the sample filter weighings. They must be the same size and material as the sample filters. If the average weight of the reference filters changes between sample filter weighings by more than ± 5µg, then the sample filter must be discarded and the emissions test repeated.

A1.2 GOLDEN PARTICLE MEASUREMENT SYSTEM AND SAMPLING SYSTEMS

The number of particles emitted by each engine technology and for each test cycle shall be determined using the "Golden Particle Measurement System" (GPMS) defined below. The majority of these components will be provided, though certain items indicated in the text shall be provided by the laboratory.

A1.2.1 Particle Sampling System

The particle sampling system shall consist of a sampling tube in the dilution tunnel (PST), a particle pre-classifier (PCF) and the GPMS particle conditioning and measurement system comprising a volatile particle remover (VPR) upstream of the particle number counter (PNC_GOLD) unit. The particle sampling system is required to draw a sample from the CVS, size classify it, transfer it to a diluter, condition the sample so that only solid particles are measured, and pass a suitable concentration of those particles to the particle counter.

A1.2.1.1 Sample Probes

A particle sampling tube shall be installed near the tunnel centre line, roughly ten tunnel diameters downstream of the gas inlet, facing upstream into the tunnel gas flow with its axis at the tip parallel to that of the dilution tunnel. The tube shall be sharp edged and open-ended and have an internal diameter of approximately 12.5 mm. The PST may be heated to no greater than 52°C.

The distance from the sampling tip to the point at which the probe leaves the dilution tunnel shall be less than 200 mm and the distance from the sampling tip to the entrance

to the particle pre-classifier unit shall not exceed 1,000 mm. The particle sampling tube shall be placed in a position equivalent to that of the probe employed for particulate mass sampling: all sampling probes and tubes shall be equally spaced about the centre line of the dilution tunnel with at least 5cm separation between them.

A1.2.1.2 Particle Pre-classifier
The upper limit of the particle size range to be measured shall be determined by the use of the cyclone particle size pre-classifier provided. The 50% cut-point of the particle pre-classifier shall lie at 2.5µm. The laboratory will provide a suitable pump capable of 90l/min (+/- 5l/min) to ensure an upper limit of particles sampled into the measurement system of ~2.5 µm.

A1.2.2 Volatile Particle Remover (VPR)
The VPR shall be used to define the nature of the particles to be measured.

A1.2.2.1 Description
The VPR provides heated dilution, thermal conditioning of the sample aerosol, further dilution for selection of particle number concentration and cooling of the sample prior to entry into the particle number counter.

A1.2.2.2 Elements of the VPR
The VPR shall comprise the following elements:

A1.2.2.2.1 First Particle Number Diluter (PND_1)
The PND_1 diluter shall be specifically designed to dilute particle number concentration and output a dilute sample equal to 150°C +/- 5°C. The diluter should be supplied with HEPA filtered dilution air and be capable of a dilution ratio range of 1 to 1000 times. For the Golden Vehicle, the dilution ratio of this diluter; $PNDR_1$ will be ~17:1 as determined by a potentiometer setting of 75%. This setting should be employed for MPI gasoline vehicles and other DPF-equipped Diesels. An initial setting of 5%-10% may be appropriate for conventional Diesel vehicles, but this should be optimised.

A1.2.2.2.2 Evaporation Tube
The ET shall be a length of tubing 240 mm +/-10 mm and I.D 6 mm +/- 0.1 mm equipped with a heating mantle. The entire length of the ET must be controlled to a temperature greater than that of PND_1, with a portion of the length equivalent to a gas residence time of 0.2 s +/- 0.05 s held at a constant temperature (+/-20°C) of 300°C.

A1.2.2.2.3 Second Particle Number Diluter (PND_2)
The PND_2 device shall be specifically designed to dilute particle number concentration. The diluter shall be supplied with HEPA filtered dilution air and be capable of a dilution ratio of ~ 10 times. The dilution ratio of this diluter; $PNDR_2$ is selected such that particle number concentration downstream the PND_2 diluter is <104 particles/cm^3 and the gas temperature prior to entry to the PNC_GOLD is <35°C.

A1.2.2.3 Performance
The VPR shall operate under conditions that achieve greater than 99% reduction of 30 nm C_{40} (tetracontane) particles and greater than 80% solid particle penetration at 30, 50 and 100 nm particle diameter.

A1.2.2.4 Location of Sampling and Measurement Equipment
The distance from the sampling tip of the PST to the entrance to the PND_1 shall not exceed 1000 mm.

The distance from the sampling tip to the point at which the probe leaves the dilution tunnel shall be less than 200 mm.

The distance from the sampling tip to the entrance to the particle number counting instrument shall not exceed 2,500 mm.

A1.2.3 Particle Counter (Particle Number Measurement Unit, PNC)
The particle counter is used to determine the number concentration of solid particles in a diluted sample of vehicle exhaust aerosol continuously drawn from the CVS.

A1.2.3.1 PNC Performance Characteristics
The particle number concentration measurement unit (PNC_GOLD) shall meet the following conditions:

- It shall operate under full flow operating conditions.
- It shall have a counting accuracy of ± 10% across the range $10^2 cm^{-3}$ to $10^4 cm^{-3}$ and +/- $10 cm^{-3}$ below this concentration against a traceable standard.
- It shall have a readability of 0.1 particles/cm^3.
- It shall have a linear response to particle concentration over 1 to 10,000 particles/cm^3.
- It shall have a data logging frequency of equal to or less than 0.5 Hz.
- It shall have a T90 response time of between 5s and 15s
- It shall have a data-averaging period of between 1 and 6s and shall not incorporate automatic data manipulation functions.

The lower particle size limit characteristics of the PNC_GOLD shall be such that the 10% (D10), 25% (D25), 50% (D50) and 90% (D90) inlet efficiencies of the instrument correspond to the particle sizes 16 nm (+/- nm), 18 nm (+/-2 nm), 23 nm (+/-3 nm and 37 nm (+/-4 nm)) respectively.

A1.2.3.1.1 Reference Particle Counter
A second particle counter (PNC_REF), with identical specification to PNC_GOLD will be transported with PNC_GOLD to act as a reference instrument. This instrument will also be operating during testing to indicate the real time function of the VPR.

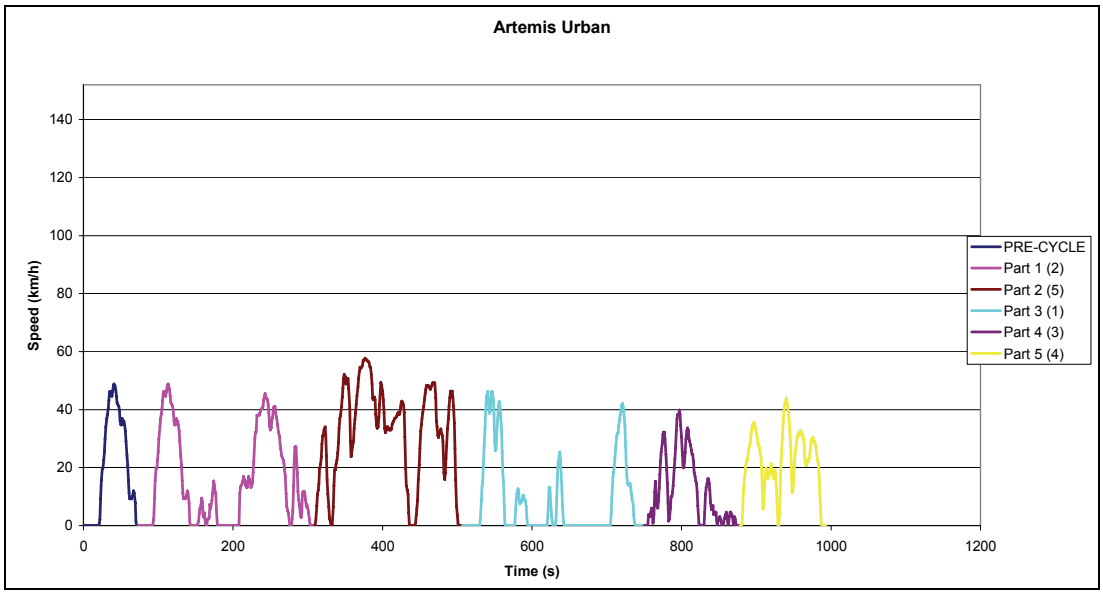
A1.2.4 Sampling lines
All sampling lines shall be either TYGON (specifically R3603), conductive silicone tubing or of stainless steel composition, contain smooth internal surfaces and be of minimal length. Sharp bends and abrupt changes in section should be avoided in all sampling lines.

Addendum 2 to TEST PROGRAMME PROTOCOL (Appendix 6)

Test Cycles

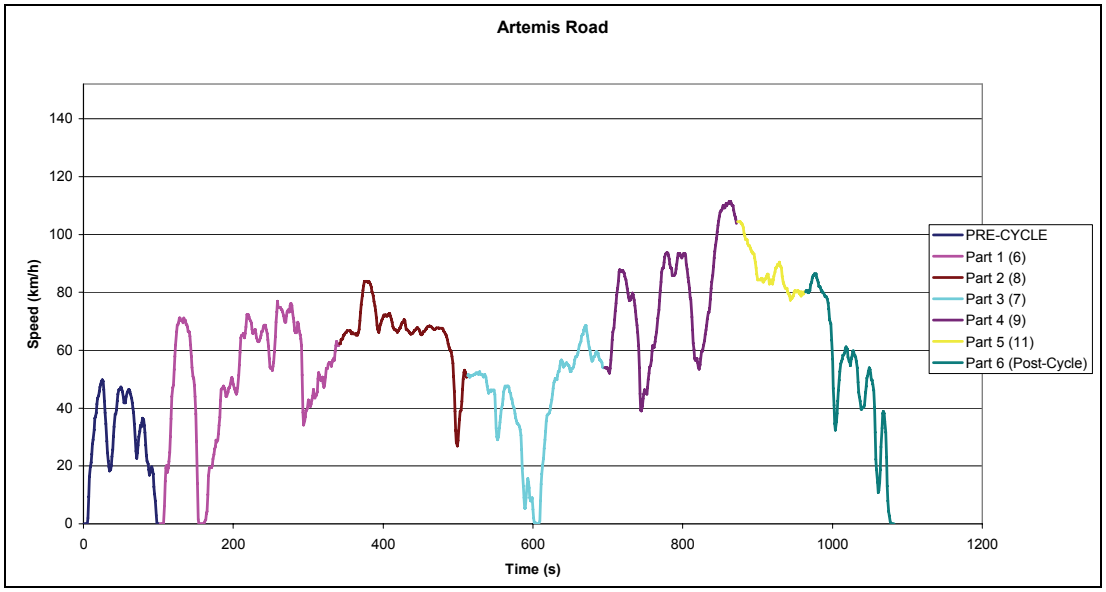
A2.1 Artemis Urban

Start of Bag sampling is to occur at 73 seconds (end of pre-cycle) and continue to the end of the test.



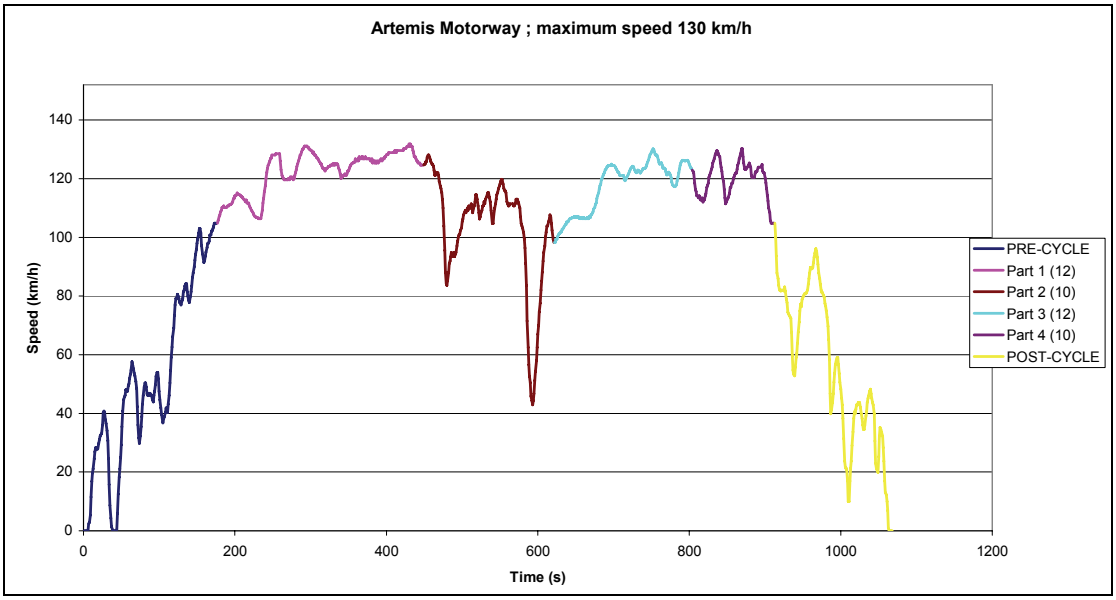
A2.2 Artemis Road (Extra Urban)

Start of Bag sampling is to occur at 102 seconds (end of pre-cycle) and continue to the end of the test, thus including Part 6 (post-cycle).



A2.3 Artemis Motorway (Highway)

Start of Bag sampling is to occur at 177 seconds (end of pre-cycle) with the end of bag sampling at 912 seconds (end of Part 4), so that it does not include the post-cycle portion.



Addendum 3 to TEST PROGRAMME PROTOCOL (Appendix 6)

Sulphur Purging or Trap Conditioning Procedures

A3.1 Diesel Vehicle E

No additional de-sulphation procedure is necessary for this vehicle, beyond the normal conditioning (3 x EUDC), as it is fitted with an oxidation catalyst.

A3.2 Diesel Vehicle F

A procedure is necessary to regenerate the particulate trap on this vehicle. This is likely to be necessary on a weekly basis. The manufacturer has suggested running the vehicle at 140 kph for a minimum of 15 minutes in 4th or 5th gear at normal road load.

A3.3 Gasoline Vehicles G and H

This procedure is based on previous procedures used to remove the accumulated sulphate from the NOx trap.

1. Run the vehicle at 130 km/h in 4^{th} gear using dynamometer load to give a catalyst-out temperature in the range 650 to 700°C.
2. Hold this condition for 10mins. Repeat this every day, prior to normal NEDC conditioning.

APPENDIX 7 ALTERNATIVE PARTICLE MEASUREMENT SYSTEM

Additional specifications of the Alternative Particle Number Measurement System used in the current study are listed below and the main details are summarized in the table.

- URG 2000-30ES Cyclone
- Dekati Fine Particle Sampler FPS 4000, with dilution air and sample probe heating, and heated Evaporation Tube.
- Grimm 5.404 Condensation Particle Counter (CPC)
- Gast Pump (90L/min)

The Dekati FPS can accurately dilute to approximately 200:1 but this level of dilution is not sufficient with a EURO III or poor performing EURO IV Diesel vehicle. For this reason, a third diluter (PND3) was introduced into the system at the recommendation of Dekati. The ejector diluter was added to the exhaust port of the Fine Particle Sampler (FPS) and its output was supplied to the Grimm CPC. The diluter was then fed a 2 bar supply of HEPA filtered air from the same source as the FPS diluters. At ambient settings, the diluter had a dilution output of 10:1.

System Property	Alternative Particle Number Measurement System
Probe	
– Type	Stainless Steel, Unshrouded
– Total Length (excluding Pre-classifier) (mm)	850
– Residence time (sec)	0.05
Pre-classifier	
– Type	URG Cyclone
– Flow Rate (l/min)	90
Transfer Tube to PND1	
– Length (mm)	400
– Diameter (mm ID)	6
– Temperature (^{o}C)	<52
PND1	
– Type	Porous tube diluter
– Temperature (^{o}C)	250
– Ratio Range	
Connection to the Evaporation Tube	
– Type	Stainless Steel
– Temperature (^{o}C)	250
– Diameter (mm ID)	8
Evaporation Tube (ET)	
– Length (mm)	600
– Diameter (mm ID)	10
– Temperature (^{o}C)	350
– Residence Time (sec)	3
– Make & Model	Dekati

PND2	
– Type	Ejector
– Temperature (^{o}C)	Ambient
– Ratio Range	
Transfer Tube to the Particle Number Counter	
– Type	Tygon
– Temperature (^{o}C)	<35
– Diameter (mm ID)	8
Particle Number Counter (PNC)	
– Make & Model	Grimm 5.404
Total System	
– Length (mm)	<3000

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