

Impact of Biodiesel Blends on Fuel Consumption and Emissions in Euro 4 Compliant Vehicles

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ABSTRACT

Fatty Acid Methyl Ester (FAME) products derived from vegetable oils and animal fats are now widely used in European diesel fuels and their use will increase in order to meet mandated targets for the use of renewable products in

road fuels. As more FAME enters the diesel pool, understanding the impact of higher FAME levels on the performance and emissions of modern light-duty diesel vehicles is increasingly important. Of special significance to Well-to-Wheels (WTW) calculations is the potential impact that higher FAME levels may have on the vehicle's volumetric fuel consumption.

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The primary objective of this study was to generate statistically robust fuel consumption data on three light-duty diesel vehicles complying with Euro 4 emissions regulations. These vehicles were evaluated on a chassis dynamometer using four fuels: a hydrocarbon-only diesel fuel and three FAME/diesel fuel blends containing up to 50% v/v FAME. One FAME type, a Rapeseed Methyl Ester (RME), was used throughout. One vehicle was equipped only with an oxidation catalyst while the other two were also equipped with two types of Diesel Particulate Filters (DPFs). In addition to CO₂ emissions, regulated tailpipe emissions (NO_x, HC, CO, PM, and PN) were collected in order to evaluate the impact of higher RME contents on emissions performance.

The results obtained over the New European Driving Cycle (NEDC) indicate that the volumetric fuel consumption systematically increases with increasing RME content for all three vehicles. Within the statistical precision, the vehicles were not able to compensate for the lower energy content of the RME/diesel blends and consumed more fuel in direct proportion to the lower energy content of the RME/diesel blends.

As the RME content of the fuel increased, the particulate mass (PM) and solid particle number (PN) were generally found to decrease over the NEDC while the NO_x, CO, and HC emissions increased. The overall impact of RME on regulated tailpipe emissions is much smaller, however, compared to the variations in emissions seen over the NEDC sub-cycles.

INTRODUCTION

The use of bio-derived blending components in road fuels is increasing around the world as a result of legislative initiatives to reduce Greenhouse Gas (GHG) emissions, reduce dependence on imported fossil fuels, and support agriculture. Within the European Union, the Renewable Energy Directive (2009/28/EC), passed by the European Parliament, mandates that 10% (energy basis) of renewable products will be required in road fuels by 2020. The European Committee for Standardisation (CEN) is already working to change the market fuel specifications in order to enable this mandate.

In the near term, biofuel obligations will most likely be met using FAME products. Although diesel blending components derived from biomass and other sources may become more readily available in the longer-term, these products are not expected to contribute substantially to the mandated EU ambitions through 2020.

Today, FAME, complying with the EN 14214 [1] specification, is most widely used as a low-level blending component in conventional diesel fuel. The current EN 590 [2] diesel fuel specification allows blending of up to 7% v/v

FAME. Many different FAME types, derived from vegetable oils and animal fats, are now in common use throughout Europe and the rest of the world. RME is most frequently used in Europe, however, and has been chosen for this study. Blends of RME in diesel fuel are described in this study by their RME content.

Of special interest is the potential impact that higher FAME contents may have on vehicle fuel consumption and regulated and unregulated emissions. Previous vehicle test programmes [3,4,5,6] have studied the effect of bio-components on both fuel consumption and emissions performance but many of the more systematic studies have focused on heavy duty engines that were not equipped with exhaust aftertreatment systems. The most comprehensive assessment of heavy-duty vehicle emissions performance was published by the US EPA [7] which showed that NO_x emissions increase and HC, CO, and PM emissions decrease as a function of increasing FAME content. More recent studies, however, on light-duty and commercial vehicles equipped with high injection pressure engines and modern exhaust aftertreatment systems suggest that the impact of FAME on pollutant emissions may not be as straightforward as considered so far [8,9,10,11,12,13,14]. For this reason, there is an overall gap in understanding on performance issues related to light-duty vehicles of importance to the European marketplace, particularly for newer Euro 4 compliant vehicles.

The fuel consumption (FC) of light-duty vehicles operating on biodiesel blends is also an important question as attention increasingly focuses on the Greenhouse Gas (GHG) savings that can be achieved from these fuel blends. In most WTW studies [15], the vehicle's efficiency is assumed not to change when the engine runs on an oxygenated fuel, that is, the same megajoules (MJ) of fuel are needed to complete a prescribed driving cycle for both hydrocarbon-only and oxygenated diesel fuels. This means, however, that a slightly higher volumetric fuel consumption is expected for oxygenated fuels because the volumetric energy content is somewhat lower than that of hydrocarbon-only fuels. This effect will be more evident as the concentration of FAME in diesel increases.

For this reason, it is important to know whether modern vehicles are capable of recovering a portion of this volumetric penalty through better engine efficiency when running on oxygenated fuels. The published literature is not entirely clear on this point, in general because there has been a greater focus on changes in emissions performance with FAME use than on fuel consumption. In addition, the energy content of FAME/diesel blends is only slightly lower than that of hydrocarbon-only diesel fuels and detecting small differences in volumetric fuel consumption can be problematic.

In order to definitively answer this question, a vehicle test programme was required that controlled experimental

variability as carefully as possible and provided sufficient statistical power to measure small differences among vehicles and fuels. Other questions also remain for modern light-duty vehicles equipped with advanced aftertreatment systems, especially the impact of higher biodiesel blends on regulated and unregulated emissions.

To address these questions, this vehicle study was designed to investigate the effect of biodiesel fuels on fuel consumption and emissions from three modern (Euro 4 compliant) light-duty diesel vehicles. All vehicles used common rail turbocharged engines and were equipped with different exhaust aftertreatment technologies.

Four fuels were evaluated in the programme. One base diesel (B0, complying with the EN 590 specification) was blended with commercially sourced RME (complying with the EN 14214 specification) to give diesel blends containing up to 50% v/v RME. Although these concentrations are higher than are allowed for today's marketplace fuels, they were selected in order to anticipate future increases in biofuel requirements and to enhance the effect of RME on vehicle performance and emissions.

This paper focuses primarily on measurements performed over the New European Driving Cycle (NEDC), the European regulatory test procedure, for both fuel consumption and regulated tailpipe emissions. All fuel/vehicle combinations were tested in a rigorously controlled and statistically designed test programme. With the exception of the PM and PN emissions, the gaseous emissions and fuel consumption were also analyzed separately for the urban and extra-urban portions of the NEDC in order to look for sub-cycle variations.

METHODOLOGY

VEHICLE SELECTION

Three modern light-duty diesel vehicles, complying with the Euro 4 emissions regulations [16,17], were specially selected for this test programme in order to test the most prominent engine and exhaust aftertreatment technologies currently present in the European diesel passenger car fleet. The characteristics of these three vehicles are described in [Table 1](#) and were tested as received without any recalibration for different FAME/diesel blends.

(See [Table 1](#) after last section of paper)

All three vehicles were equipped with direct injection (DI) common rail diesel engines and were equipped with exhaust gas recirculation (EGR) for NO_x control and a diesel oxidation catalyst (DOC) for reducing CO and HC emissions. Vehicles 1 and 3 were also equipped with diesel particle filters (DPF) for PM emissions control. The regeneration

strategies for these DPF systems were different. Vehicle 1 was equipped with a catalysed DPF while Vehicle 3 used a fuel-borne catalyst and in-cylinder injection to periodically regenerate the DPF. Although different FAME types can impact soot loading and DPF regeneration, this was not the focus of this study and DPF regenerations were explicitly avoided during measurements.

The average emissions over the NEDC are shown in [Figure 1](#) for all tests on the hydrocarbon-only diesel fuel (B0). Compared to the Euro 4 emissions limits shown by the horizontal bars, all three vehicles complied with Euro 4 limits, although the NO_x emissions for Vehicle 3 and PM emissions for Vehicle 2 were borderline. The DPF-equipped vehicles (Vehicles 1 and 3) reduced the PM emissions to levels that were substantially lower than that required even by the upcoming Euro 5 emissions regulation [18].

(See [Figure 1](#) after last section of paper)

A single lubricant was used in all three vehicles in order to eliminate the influence of different lubricants on engine performance and emissions. The lubricant was an SAE grade 0W-30 intended for diesel engines (ACEA Class B3-B5) with low sulphur, phosphorus, and ash contents.

DIESEL FUEL PROPERTIES

Four fuels were selected for this study: a diesel fuel (B0) and 3 blends of B0 with RME. The B0 fuel complied with the European EN 590 specification and the RME blend component complied with the European EN 14214 specification. Although most FAME products used in Europe are blends of different FAME types, RME is the single most commonly and was selected for this test programme. The RME contained 1,000ppm of butylated hydroxytoluene (BHT) antioxidant in order to ensure acceptable oxidation stability throughout the test programme.

The RME was blended into the B0 fuel at three different concentrations, resulting in the following four fuels:

- B0: Hydrocarbon-only diesel fuel
- B10: 10% v/v RME in B0
- B30: 30% v/v RME in B0
- B50: 50% v/v RME in B0

A fully-formulated diesel performance additive package that is widely used in Europe was added to all test fuels at the same concentration in order to ensure fuel system cleanliness throughout the vehicle test programme. The oxidation stabilities of the RME/diesel blends were also monitored throughout the test programme using the Rancimat oxidation test (EN 15751). Compared to the results on the fuel blends at the start of vehicle testing, the measured oxidation stabilities

decreased by no more than 8% by the end of the vehicle testing programme for all RME blends.

The properties of these four test fuels and the RME blend component (B100) are summarized in [Table 2](#) and in [Appendix A](#).

(See [Table 2](#) after last section of paper)

As shown in [Table 2](#), increasing the RME content from B0 to B50 resulted in a small (7%) reduction in LHV. For this reason, the test protocol was carefully designed with sufficient statistical power in order to control experimental variability and to differentiate between small differences in FC and regulated emissions.

EXPERIMENTAL PROTOCOL

A standardized daily test procedure was essential for controlling variability and for measuring small differences in fuel consumption and emissions between fuels and vehicles. A schematic of the test protocol is provided in [Appendix B](#).

Before the first test on a vehicle, the lubricant was changed and the vehicle was driven for 1000km in order to age the lubricant. During this mileage accumulation, information was collected on the DPF-equipped vehicles in order to monitor the DPF regeneration frequency and to ensure that any DPF regenerations would occur outside of the daily test procedure.

Before the daily test procedure, the vehicle was pre-conditioned on the designated test fuel and was cold soaked overnight. The daily test protocol collected fuel consumption and emissions measurements in the following sequence:

- New European Driving Cycle (NEDC, see [Figure 2](#)) on the cold vehicle consisting of the:
 - Urban Driving Cycle (UDC, also called the ECE-15),
 - Extra Urban Driving Cycle (EUDC),
- ARTEMIS transient cycle consisting of the Urban and Road portions [[19](#)],
- Two steady-state conditions at 120 and 50km/h.

The ARTEMIS and steady-state results are not presented in this paper, however.

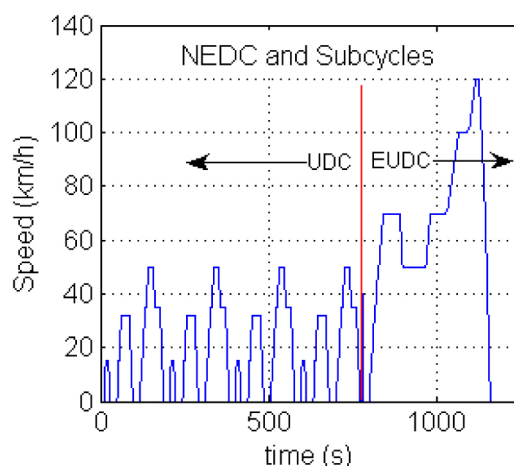


Figure 2. Schematic of the NEDC and UDC/EUDC Sub-cycles

Strict adherence to the daily protocol ensured that all vehicle preparation, fuel changes and vehicle measurements were carried out in a repeatable manner for each vehicle/fuel combination. The RME-containing fuels were tested four times in each vehicle and the B0 fuel was tested five times in order to obtain improved estimates of baseline performance and engine drift. A typical test order is shown below:

Test	1	2	3	4	5	6	7
Fuel	B0	B10	B50	B30	B0	B10	B30

Test	8	9	10	11	12	13	14
Fuel	B50	B0	B50	B30	B10	B0	B10

Test	15	16	17
Fuel	B50	B30	B0

The RME-containing fuels were tested in four randomized blocks with the B0 runs positioned between each block and at the start and end of testing. Different randomized orders for the RME-containing fuels were used for each vehicle. The block design approach helped to eliminate potential sources of variability and ensured that no back-to-back measurements were made on the same fuel. Seventeen days of testing were required to complete testing on one vehicle and a single driver was used for all vehicle tests.

A repeat test criterion was included in the test protocol if the variation in FC test results exceeded expected levels. If the ratio of the highest to the lowest fuel consumption measurement over the cold NEDC for a particular vehicle and fuel combination exceeded 1.05, then a repeat test was to be conducted on that vehicle and fuel as soon as possible or at the end of the test programme. This criterion was based on

historical repeatability data from various sources. In this study, the variation in FC results did not exceed this ratio and no repeat tests were required. Similar criteria were not set for the other tailpipe emissions and cycles.

In addition to the typical measurements used to monitor the engine and vehicle operation, the following pollutants were measured over the NEDC:

- CO₂ exhaust emissions from which the volumetric fuel consumption was calculated,
- NO_x, CO, and HC emissions, and
- PM and PN emissions.

The PN emissions were measured according to the Particle Measurement Programme (PMP [20,21]) protocol and correspond to the total number of solid particles.

Emission measurements over the NEDC were conducted following the European regulations. Exhaust gas was first diluted and conditioned by means of Constant Volume Sampling (CVS) in which a 6m long corrugated stainless steel tube transferred the exhaust from the tailpipe to the CVS tunnel inlet. This tube was insulated in order to minimize heat losses and particle thermophoresis and was clamped onto the vehicle exhaust pipe with a metal-to-metal connection to avoid exposing the hot exhaust gas to any synthetic material connectors. A flow rate of approximately 500 Nm³/h was maintained in the CVS tunnel by a positive displacement pump. The dilution air was filtered through a HEPA class H13/EN 1822 filter at the inlet of the dilution tunnel. Proportional diluted exhaust samples were collected in bags for subsequent measurements.

The gaseous pollutants in the bag samples were measured with common laboratory analyzers as required by European legislation (chemiluminescence for NO_x, a flame ionization detector for HC, and non dispersive infrared for CO and CO₂). Fuel consumption was derived by means of the exhaust-to-fuel carbon balance (Appendix C), taking into account the oxygen content of fuels. PM samples were collected on 47mm PTFE-coated glass fibre filters (Pallflex TX40HI20-WW) following the PMP specifications. The particle sampling system also followed the latest PMP recommendations and consisted of a metallic tube (probe) sampling directly from the dilution tunnel. This probe was directly connected to the particle transfer tube, a particle pre-classifier (cyclone) and a measurement system comprising a volatile particle remover (VPR) upstream of the particle number counter unit (CPC 3010, TSI).

RESULTS

FUEL CONSUMPTION (FC)

The primary objective of this study was to determine whether modern vehicles improve their efficiency when running on RME/diesel fuels. If this were to occur, the volumetric FC will be lower than predicted based solely on changes in the LHV of the RME/diesel fuel blends. Since the changes in LHV are not large, however, higher RME contents and a rigorous test protocol were used in this study.

Although both CO₂ emissions and FC have been determined, changes in engine efficiency as a result of the RME content will be better reflected by changes in the CO₂ emissions rather than by changes in FC. This is primarily because CO₂ emissions are directly measured. The FC depends on the measured CO₂ emissions and on changes in the properties of the fuel itself, both of which have experimental uncertainty. In this sense, CO₂ emissions results can be linked to improvements or deterioration of combustion efficiency and are very important in terms of a WTW analysis.

Figures 3 and 4 show the CO₂ emissions and fuel consumption results, respectively, for all vehicles over the UDC and EUDC sub-cycles of the NEDC as well as for the full NEDC. In all of the bar charts in this study, the error bars represent $\pm 1.4 \times$ the standard deviation of the mean value for the indicated fuel and vehicle. The 1.4 factor was selected for consistency with the EPEFE Programme [22] and with previous CONCAWE studies [23,24,25]. Emissions from two different fuels will not be significantly different from one another at $P < 5\%$ unless there is a sizeable gap between their error bars³.

(See Figure 3 after last section of paper)

(See Figure 4 after last section of paper)

As shown in Figures 3 and 4, the variation in repeat CO₂ emissions measurements was about ± 2 -3% and within the range expected for such measurements. Increasing the RME content generally increased the CO₂ emissions as would be expected from the lower energy content of the RME/diesel fuel blends. It is clear, however, that the CO₂ emissions and FC depend much more significantly on the NEDC sub-cycle than on the fuel composition.

Focusing on the fuel variations only, however, the CO₂ emissions are slightly higher for the B30 and B50 fuels while the effect of B10 was sometimes not statistically significant for some vehicle and cycle combinations. All vehicles responded in a similar way with increasing RME content for

³ $P < 5\%$ = 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 observed effect is real.

CO₂ emissions and FC. For Vehicle 3, however, the CO₂ emissions, especially over the UDC sub-cycle, appeared to be lower for B10 and then increased again with the B30 and B50 fuels. The FC and CO₂ results followed similar trends for all vehicles and cycles.

Over the NEDC, the vehicle is driven according to a prescribed cycle of speed versus time (see [Figure 2](#)). For fuels having different LHVs, this means that different masses of fuel will be consumed over the regulatory cycle and converted to CO₂ exhaust emissions through combustion. As the RME content increases, two effects act in different directions on the CO₂ emissions and volumetric FC:

- Increasing the RME content of the fuel (decreasing the LHV of the RME/diesel fuel blend) will increase the mass of fuel consumed. In the absence of other effects, this will tend to increase the overall CO₂ emissions.
- Increasing the RME content of the fuel also increases the oxygen content and decreases the carbon content. In the absence of other effects, this will tend to decrease the overall CO₂ emissions.

Considering the relative size of these two effects, an overall increase in the volumetric FC is still expected for the RME/diesel fuel blends compared to B0 but by a smaller percentage than would be expected based on the change in the fuel's energy content alone. Since the predicted FC depends on the volumetric lower heating value (VLHV), a plot of % change in measured FC versus the % change in $[1/\text{VLHV}]$ can be used to compare the measured FC changes to the predicted FC changes for different fuels. Details on the FC calculations for the RME/diesel fuel blends are provided in [Appendix C](#).

This analysis was completed for the NEDC and the results are shown in [Figure 5](#). The left-hand charts show the change in measured FC (in 1/100km) versus the VLHV (in MJ/l) of the test fuel for all three vehicles over the NEDC. The error bars represent the accumulated error and the solid line is a best fit through the data points. The correlation between the FC and VLHV is obviously very good.

In the right-hand charts, the percent change in measured FC is plotted versus the percent change in $[1/\text{VLHV}]$ using the average B0 results for each vehicle as the basis. The error bars represent ± 2 times the standard deviation of the percent change for each vehicle and fuel based on the repeatability of multiple FC measurements. The solid line is a best fit regression through the origin fitted to the B10, B30, and B50 data points and the slope of this line is shown on the chart. The dotted lines above and below the solid line show the 95% confidence limits for the best fit regression line. Finally, a one-to-one correlation line is also included as a dashed line in each figure.

(See [Figure 5](#) after last section of paper)

In the right-hand charts, if the best fit line falls on or above the one-to-one correlation line, then the engine is not achieving better than expected efficiency on the oxygenated fuels. Within the experimental uncertainty inherent in the measurements, the data show that the FC correlates with the loss in energy content of the fuel.

Especially for Vehicles 1 and 2, there is some evidence that the engine efficiency over the NEDC is actually reduced on the higher biodiesel fuels, that is, the best fit lines lie above the one-to-one correlation lines for two of the three vehicles. However, the best fit lines and the one-to-one correlation lines are not outside the 95% confidence limits.

The data show that the volumetric FC is proportional to the energy content of the RME/diesel blend over the NEDC cycle. There is no evidence that the use of RME as a blending component for diesel fuel provides a volumetric FC benefit, at least in the Euro 4 vehicles and NEDC used in this study. The engine management systems in these vehicles are not able to compensate for the lower energy content of the RME/diesel fuel blends through better engine efficiency on the oxygenated fuels.

It should also be noted that volumetric FC is usually reported by vehicle manufacturers and researchers because it is a regulated number intended to provide consumers with an understandable indicator of a vehicle's efficiency over a typical driving cycle. As was used in this study, CO₂ emissions are also suitable for evaluating a fuel's sustainability and environmental impact and reflect the parameters of interest, namely engine efficiency and CO₂ emissions.

REGULATED EMISSIONS

In addition to the FC data, the regulated pollutants were also measured and used to evaluate the impact of RME on emissions. In each case, the average values recorded over each cycle are plotted with error bars representing ± 1.4 times the standard deviation of the average.

NO_x Emissions

[Figure 6](#) shows the NO_x emissions measured from each vehicle over the NEDC.

(See [Figure 6](#) after last section of paper)

From the NO_x emissions results in [Figure 6](#), it is observed that increasing the RME content of the fuel generally increases the NO_x emissions, in some cases, by up to 20% for the B50 fuels. The NO_x emissions from the B10 fuel were not significantly different from those with the B0 fuel. For

the B30 fuels, however, the increase in NO_x emissions was in the 1-10% range, depending on the fuel blend and vehicle, and statistically significant from the B0 fuel results in most cases.

Over the NEDC, all three vehicles responded in a similar way with the NO_x emissions increasing as the RME content of the fuel increased. Over the NEDC sub-cycles, however, Vehicles 1 and 3 responded quite differently, with Vehicle 1 giving higher NO_x emissions over the UDC and Vehicle 3 giving higher NO_x emissions over the EUDC. These differences were much larger than the effects found with changing RME content.

In Vehicle 2, however, the NO_x emissions over the UDC were essentially unchanged for all four fuels but did increase slightly over the EUDC with increasing RME content. Since the differences found in the sub-cycles gave similar results for all vehicles across the NEDC, it is possible that the sub-cycle differences are associated with different engine management strategies in all three vehicles.

Overall, the effect of increasing FAME content on NO_x emissions from the light-duty diesel vehicles in this study is directionally consistent with that reported previously for heavy-duty [7] and light-duty vehicles [26,27,28,29].

CO and HC Emissions

The carbon monoxide (CO) and hydrocarbon (HC) emissions from each vehicle are shown in [Figures 7](#) and [8](#), respectively, over the NEDC.

(See [Figure 7](#) after last section of paper)

(See [Figure 8](#) after last section of paper)

From [Figures 7](#) and [8](#), the absolute emissions levels from all vehicles were well below the Euro 4 regulatory limits. Nevertheless, there is a general trend of increasing emissions with RME content except in the EUDC sub-cycle where the emissions were very low after the DOC had fully warmed up.

For all vehicles, the presence of RME increased the CO and HC emissions over cold start by about 70%. Over the NEDC, the CO and HC emissions are primarily due to emissions occurring over the UDC portion of the NEDC. Compared to the UDC, emissions over the EUDC are very low due to the presence of the DOC and are close to background levels.

Similar observations regarding cold start emissions performance are mentioned in other studies [10,30] and contradict the usual expectation that biodiesel reduces CO and HC emissions. From the results presented here, RME increases the tailpipe CO and HC emissions with increasing RME content and the effect is larger over the UDC cold start

condition. More work would be needed to better understand the cause of this effect.

PM EMISSIONS

[Figure 9](#) shows the particulate mass (PM) emissions for all vehicles over the NEDC.

(See [Figure 9](#) after last section of paper)

From [Figure 9](#), the absolute PM emission levels of the DPF-equipped vehicles (Vehicles 1 and 3) were very low and in some cases close to the measured background. For Vehicle 2, the PM emissions for the B0 fuel were 40-50 times higher than those from the DPF-equipped vehicles and the PM emissions decreased with increasing RME content. Over the NEDC, reductions of up to 50% were observed with the B50 fuel. The effects of increasing FAME concentration on PM emissions from light-duty diesel vehicles are generally consistent with those reported in the existing literature.

Particle Number (PN) Emissions

Ultrafine particle emissions are of increasing concern due to their impact on both air quality and health. There have been many investigations into the measurement of the number (and type) of particles emitted from automotive vehicles [23,24,25,31-32]. Under the auspices of the UNECE GRPE, a 'Particle Measurement Programme' (PMP [20]) was put in place to develop a standard protocol which measures dry (solid) particles following the removal of volatile material from the exhaust stream. Measurement of PN concentrations has also been added to the EU's light-duty vehicle emissions regulation with a compliance limit of 6×10^{11} particles/km. For this study, the total number of 'solid' particles was measured using a PMP compliant procedure.

[Figure 10](#) shows the logarithmic means for the PN emissions measured from each vehicle. As per the PMP procedure, the PN was measured over the NEDC and not over the UDC and EUDC sub-cycles. PN levels lower than about $1\text{E}+09$ are generally within the background levels of the test laboratory.

(See [Figure 10](#) after last section of paper)

Although some of the PN results on Vehicles 1 and 3 are close to the background level, it is clear that the DPFs successfully reduce PN at the same time that they reduce PM levels and there is little evidence for RME effects on these results. For Vehicle 2 without DPF, the absolute PN levels are much higher and depend somewhat on the RME content, with lower PN levels observed as the RME content increases. The reductions are not large, however, compared to those due to the DPF equipment.