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Particulate Matter Emissions from a Heavy Duty Vehicle Fuelled By Petroleum Diesel and Used Cooking Oil Blends

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Abstract

Fuel characteristic and exhaust particulate emissions tests were carried out for a EURO5 compliant Heavy Duty Vehicle operating on both pure petroleum diesel (PD) and used cooking oil (C2G Ultra Biofuel) PD blends under real world driving conditions. Fuel tests showed that fuel temperature, substitution ratio and engine speed play a key role in determining the spray characteristics of the Ultra Biofuel blends. However, under real world operating conditions, the Bioltec fuel blending system was found to overcome these effects by using lower C2G Ultra Biofuel:PD substitution ratios during cold start and low speed conditions. Overall the fuel tests suggested it to be convenient to operate the engine on blends with Ultra Biofuel content up to 80% to avoid higher fuel consumption and higher pollution load on the exhaust after treatment system, particularly at low temperatures and rpm. In the real world tests, average substitution ratios of 85% were achieved, with close to 100% Ultra Biofuel achieved for high speed steady state conditions, with no negative impact on particulate emissions. The vast majority (60-80%) of the particulate mass within the exhaust was found within size fractions below 2.5 μm for both fuels and was thus within the respirable range. The PD produced around twice the concentration of particulates within these finer fractions compared to the equivalent trips using the blended fuel. Thermo-gravimetric Analysis demonstrated that the PD produced higher concentrations of black carbon (soot) and the Ultra Biofuel blends more organic carbon within the particulates. The tests demonstrate that when using an effective fuel substitution strategy, Ultra Biofuel has the potential to reduce both lifecycle CO₂ and respirable particulate emissions leading to potential climate and air quality benefits.

Introduction

The ever increasing consumption of conventional fossil fuels has caused serious concerns about climate change and energy supply security issues. The transport sector is one of the major CO₂ producers, accounting for about a quarter of total global CO₂ emissions with road transport dominating [1]. Heavy Duty Vehicles (HDVs) are the second biggest source of CO₂ emissions, contributing about 25% of the emissions from the sector. The increase in road freight via HDVs means that their CO₂ emissions are still rising despite improvements in fuel efficiency over the last few years. This therefore calls for urgent measures to tackle CO₂ emissions from this sector, a fact not lost on the European Commission (EC) in its Strategy on Clean and Energy Efficient Vehicles, of 2012 [1].

Biofuels as a means to reduce the carbon footprint of road transport have attracted great attention during the last decade. Biodiesel is one of the major biofuels in Europe. The application of biodiesels in diesel engines is a relatively mature technology in terms of production and combustion in diesel engines. In general, biodiesels can burn well in diesel engines and produce lower CO, hydrocarbon and particular matter (PM) emissions compared to petroleum diesel (PD) [2-8]. However, the potential for carbon reduction by biodiesels depends on both feedstock and production processes. Currently biodiesels produced in the EU are mainly derived from edible vegetable oils as feedstock such as rape seed oil [9, 10]. These biodiesels (first generation) are often the subject of public debate due to their effects on rising food prices and the competition between land use for biodiesel feed stocks vs. the cultivation of food crops. Second generation biofuels use non-edible biomass such as lignocellulose as the feedstock to produce synthetic

diesel fuel, but the cost of the production process is high. Thus attention has been diverted to using Used/Waste Cooking Oil (UCO or WCO) as a feedstock [11, 12] since it offers easier acceptance by the public with regard to ethical issues, is more economically viable and contributes to sustainable waste management practices. In the UK, UCO's contribution to total biodiesel production reached 66% in 2012-13 [13].

However, converting UCO into biodiesel involves a trans-esterification process, in which the carbon footprint of methanol is brought into the fuel chain. This factor, along with the demand for extra energy for the process and a typical yield of 90%, reduces the carbon reduction potential of UCO derived biodiesel. Esteban et al. [14] assessed the advantages of the use of SVO (Straight Vegetable Oil) directly as a biofuel versus biodiesel and showed a clear preference for SVO compared to biodiesel. Peiró et al. [15] conducted a Life Cycle Analysis assessment for a used cooking oil based biodiesel and found that the trans-esterification stage accounted for 68% of the total environmental impact.

Disadvantages of using SVO and UCO instead of biodiesel can arise however, due to differences in fuel properties and spray characteristics when compared to PD. Some of these problems may be alleviated through heating and/or fuel blending or substitution to ensure proper fuel spray and mixing and to meet emission requirements. For example, an EU project (2nd Veg Oil) involving John Deere, reported a successful demonstration program of using PPO (Pure Plant Oil) in TIER4 tractor diesel engines [16]. Several studies demonstrated that when SVO is heated, satisfactory combustion and emission performance could be achieved [17-19]. Fontaras et al. investigated emissions from

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passenger diesel cars using SVO-diesel blends over legislated and real world driving cycles [20]. They tested three vegetable oils (cottonseed, sunflower and rapeseed) blended with diesel at 10-90% v/v ratios. They reported a mixed picture on emissions, implying that the impact of SVO on emissions will vary dependant on driving cycles. Their results showed that in general SVO can reduce exhaust PM but could increase hydrocarbon emissions.

These studies all used SVO but to date very few studies have focused on real world emissions from UCO blends under real world conditions, particularly for HDVs. This work therefore examines the environmental impacts of the direct use of refined straight UCO (C2G Ultra Biofuel) within diesel engine powered 44 tonne trucks, focusing on particulate emissions. Ten trucks within the United Biscuits (UB) Ltd. distribution fleet have been converted to be able to burn the Ultra Biofuel with an on-board fuel substitution Biotec system. A dual fuel tank containing the Ultra Biofuel and PD has been fitted to each truck. The Biotec system is a microcomputer controlled automatic fuel selection and blending system, which can select fuel supply (PD or the Ultra Biofuel) and adjust the substitution ratio based on certain measured engine operational parameters such as fuel temperature and load [21]. Fuel characteristics and consumption, engine deposits, exhaust emissions, lube oil aging and operational performance have been monitored within the project. This paper focusses on fuel properties, jet characteristics and comparative exhaust particulate emissions between the use of PD and the C2G Ultra Biofuel blends under real world driving conditions.

The fuels used and their properties

Standard PD complying with EN590 was used either in neat diesel mode as a baseline or in blended mode. The C2G Ultra Biofuel (a fully renewable fuel made as a diesel replacement from processed used cooking oil, used directly in diesel engines specifically modified for this purpose) as a non-trans-esterified biofuel to be tested was produced and supplied by Convert2Green Ltd. Table 1 presents selected physical and chemical properties of the C2G Ultra Biofuel and PD fuels. The C2G Ultra Biofuel has much higher kinematic viscosity than PD, which may affect fuel spray and mixing if there are no proper measures to reduce its viscosity. The mass based calorific value of the C2G Ultra Biofuel is about 10% lower than PD but the volumetric calorific values for both fuels are almost the same. The C2G Ultra Biofuel contains ~11% by mass of oxygen which could assist the combustion of the C2G Ultra Biofuel. Oxygenated fuels have less carbon to carbon bonds with a higher premixed combustion temperature and it has been previously shown that they soot less than PD. Investigation of the combustion of the oxygenated fuels has previously revealed reduced soot precursor formation in the rich premixed flame zone and a better polycyclic aromatic hydrocarbon (PAH) oxidation by OH radicals [22].

A dual fuel tank with a split of 300 litre for the C2G Ultra Biofuel and 160 litre for PD was retrofitted to trucks. A fuel-engine coolant heat exchanger was

inserted to the biofuel tank side, which is part of an on-board fuel blending system-Biotec system. The C2G Ultra Biofuel in the tank was heated by the engine coolant to approximately 25-40 °C depending on ambient temperature, and transported from the tank to the Biotec fuel control module and heated further to 60-80 °C.

The Biotec system has the capability to manage the fuel blend, supplying to the engine based on the engine's operational conditions, i.e. the engine's load and warm up status. 100% PD will be supplied to the engine during cold start and idle conditions, while 100% C2G Ultra Biofuel will be fed into the engine if the engine is hot and at high load. Blended fuel from PD and the C2G Ultra Biofuel will be supplied proportionally to the engine in the case of partial load.

Table 1- Selected physical and chemical properties of the C2G Ultra Biofuel and PD fuels

Fuel Properties	C2G Ultra Biofuel	PD
Viscosity@ 40 °C, mm ² /s	35	2-4.5
Density (kg/m ³)	920	840
Carbon %	76	87
Hydrogen %	12	13
Oxygen %	12	0
Calorific Value (MJ/kg)	39	43
Calorific Value (MJ/L)	36	36

Fuel jet and droplet characteristics

Optical observations of fuel jet penetration and flame lift off and propagation have been shown to play a key role in understanding PM genesis, growth and diminution during engine combustion. For example, soot survival is possible if the flame length extends to hit the combustion chamber walls leading to both deposits and exhaust emissions. Poor fuel atomisation can also lead to the formation of larger soot particles [23]. The high fuel injection pressures used in modern engines help to reduce the mean droplet size, increase the jet cone angle and reduce fuel jet penetration length, as well as enhancing fuel evaporation rates [23]. These features should help to reduce soot emissions but will also be dependent on fuel characteristics [24].

The significantly higher fuel viscosity of the Ultra Biofuel could reduce the spray cone angle and increase the penetration length as well as affecting droplet size and reducing the fuel flow rate due to the increased friction coefficient [25]. All of these factors could affect particulate emissions as discussed above. Figure 1 shows that the kinematic viscosity of the blend increases dramatically as the Ultra Biofuel content in the blend increases above 80%, even at higher temperatures. It also illustrates the impact of these changes in viscosity on predicted fuel jet length and Sauter Mean Diameter (SMD) for different fuel blends, engine speeds and temperatures. The approach taken is fully described in

Dizayi et al. [26] and follows a modelling approach developed by Wakuri et al. [27] based on momentum theory for jet length and that of Dernothe et al. [28] for SMD.

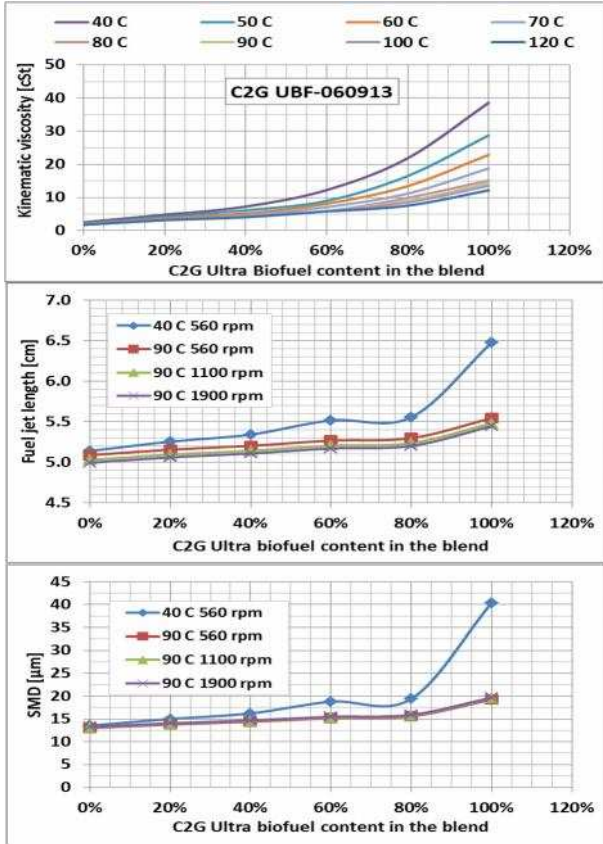


Fig. 1 Variation of kinematic viscosity ν_f , fuel jet length, and SMD with C2G Ultra Biofuel content in the blend at different temperatures and engine speeds.

It is clear from Fig. 1 that at lower temperatures, fuel blends of above 80% Ultra Biofuel give rise to increased fuel jet length and droplet sizes, and hence may have an impact on both engine deposits and exhaust particulates. At higher temperatures and engine speeds however, the difference between even 100% Ultra Biofuel and PD is reasonably small. The on board blending system should be able to compensate for these differences by adjusting the substitution ratios during low temperature start up, idle and low engine speeds as discussed within the next section.

Real world fuel analysis

The test vehicle is a 44 tonne articulated truck, categorized as a Euro V emissions compliant vehicle. The fuel system of the tractor was modified to be able to burn both C2G Ultra Biofuel and PD. The tractor (Mercedes-Benz Axor C 2543) is powered by a DICI turbo-charged 6-cylinder in-line diesel engine (OM457 LA). Engine specifications are detailed in Table 2.

The driving route was selected from one of the routine delivery journeys travelled by the UB trucks on a daily basis. It consists of urban travel (frequent stops and starts in urban areas) and high speed cruising on UK major

roads and motorways. Hence, both low speed congested and high speed free flow travel under real world driving conditions can be represented. The journeys started from Ashby De La Zouch and ended at Wigston and vice versa. The single trip distance is about 35 km. A Race Logic differential GPS system was installed on-board to record and log the vehicle's velocity, altitude, location and headings (directions, degree from north).

Table 2 - Engine type and specifications

Engine parameters	Value
Engine model	OM 457 LA EURO 5
No. of cylinders	6 in line
Displacement	11.97 [Litre]
Bore	128 [mm]
Stroke	155 [mm]
Compression ratio	18.5
Rated power	315 kW at 1900 rpm
Maximum torque	2100 Nm at 1100 rpm
Injection pressure, Max.	1800 [bar]
Number of injection holes	7
Injector hole diameter	200 [μm]

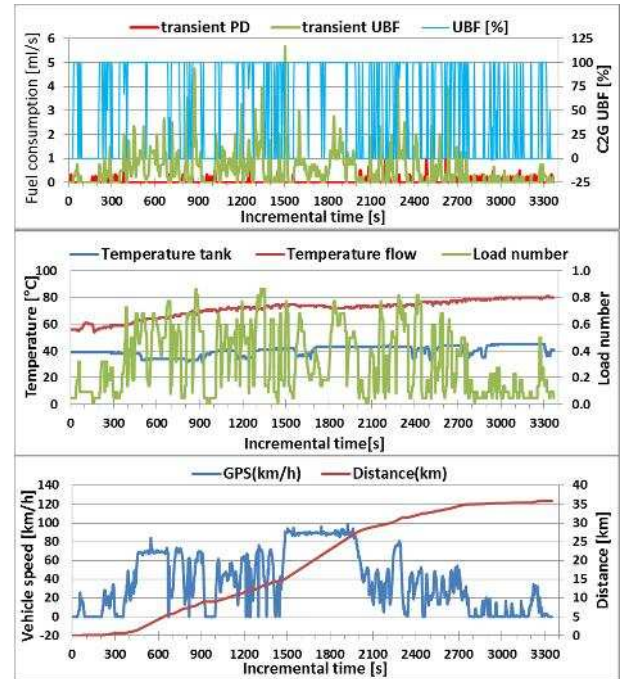


Fig. 2 Fuel consumption, fuel temperature variation, normalised load number, vehicle speed variation and cumulative distance along a particular journey from Ashby De La Zouch to Wigston.

Data from the Bioltec and GPS systems were plotted against travel time as shown in Fig.2. This trip was carried out during a sunny afternoon where the ambient temperature was 11°C, atmospheric pressure was 103.4 kPa and the wind speed was 13km/h from the East. The trailer was empty. Transient fuel consumption analysis showed an average substitution ratio of 79.8% for the journey demonstrating an engine propensity to use more C2G Ultra Biofuel than PD within the blend. Data

collected from all systems indicates an average substitution ratio of 85% based data from 10 HDVs over a period of one year. The peaks and fluctuations in C2G Ultra Biofuel consumption correlate reasonably well with variations in load number which a dimensionless parameter indicating the instantaneous changes of the external load exerted on the engine. Engine demand for PD increases at the start of the journey and during low gear ratios where a higher energy is demanded. Previous research by United Biscuits Ltd. has shown the most fuel efficient speed to be 82km/h and hence this is the maximum speed achieved during the journey due to limits imposed. The average speed for this journey was 36.6 km/h. The fuel tank temperature was kept nearly constant at around 40°C by heat recovery from the cooling system. However, the fuel temperature continued to increase to stabilise at 80°C due to fuel circulation from the return lines. Figure 1 showed that at temperatures above 80°C, the viscosity, jet length and droplet diameter of the blended fuels was reasonably consistent with that of PD even at high fuel substitution ratios. Thus under real world driving conditions, the fuel blending system seems to be able to maintain consistent fuel quality.

Exhaust Particulate Sampling

Particulate matter (PM) samples were taken from the exhaust tail pipe through two stainless steel pipes 6.36 mm diameter each connected to an insulated Teflon tube to the driver's cabin. PM samples were taken using two systems: a PM_{2.5} total mass measurement (Andersen Impactor 1) and size segregated measurements below PM₁₀ using an 8 stage Andersen Impactor (Andersen Impactor 2). The PM_{2.5} total mass measurement utilized the pre-separator and backup stage of an Andersen Impactor to collect particles. The exhaust samples first travelled through an ice trap to remove water vapour and then passed through a PM_{2.5} cyclone to remove particles larger than 2.5 microns.

The Andersen Impactor 2 consisted of a pre-separator and 8 aluminium stages including seven impact stages and a backup stage. The function of the pre-separator is to remove particles larger than 10 micron (>PM₁₀). The stage numbers and their particle size ranges, each based on a D50 cut-off i.e. the size at which the collection stage has 50% efficiency, are illustrated within Table 5. The sample flow rate for each Impactor was controlled according to the manufacturer's specifications.

Preconditioned glass fibre (GF/F) filter papers were used as a substrate to collect PM samples so as to enable further analysis. After each test the loaded filter papers were saved individually in petri dishes and then wrapped in a plastic bag and refrigerated. All loaded filter papers were desiccated for at least 24 hours before re-weighing in order to evaluate particulate mass emissions. Blank filter papers also underwent the same procedure, apart from sampling, in order to correct for any changes in conditions. The Andersen Impactors and the pre-separator were wrapped in a temperature controlled heating jacket to maintain the combination at a constant

temperature of 50°C according to SAE standards for PM sampling procedures. Samples were taken along the 70 km delivery journey from Ashby De La Zouch to Wigston and back.

After the mass emissions tests, portions of filter samples were analysed for elemental carbon (EC), volatile organic fraction (VOF), and ash content by Thermo-gravimetric analysis (TGA).

Results of Particulate Sampling

Single stage filter unit

Table 3 shows the average PM_{2.5} exhaust mass concentrations for each journey for the PD and blended fuel tests with empty and loaded trailers respectively. Results showed that the use of C2G Ultra Biofuel blends can reduce PM emissions by 65~75% compared to the use of PD. The repeatability of the data was good, as shown by the fairly low standard deviation (SD)/mean percentages. The significant reduction of PM by the blends is considered to be due to the fuel born oxygen, which assists the oxidation of the soot in the combustion chamber. Since the on board blending system avoids the use of high substitution ratios at low engine speeds and fuel temperatures (see Fig. 2), the potentially negative effects of the high fuel viscosity at lower temperatures seem to be avoided. The PM emissions do not seem to be sensitive to engine load conditions, or operation with an empty or loaded trailer.

Table 3 Comparison of trip average emissions for PM_{2.5} (mg/m³) for diesel only (PD) and blended fuel trips

Trip number	Empty trailer		Loaded trailer	
	Av speed [km/h]	PM [mg/m ³]	Av speed (km/h)	PM [mg/m ³]
PD trip 1	42.1	2.08	42.7	2.02
PD trip 2	51.3	1.99	42.8	1.28
PD trip3	36.0	1.68	38.0	1.55
PD Mean	43.1	1.92	41.2	1.62
SD		0.21		0.37
SD/mean %		0.11		0.23
Blended Fuel trip 1	45.7	0.42	42.3	0.49
Blended Fuel trip 2	49.5	0.56	45.6	0.60
Blended Fuel trip 3	41.8		39.8	0.69
Blended Fuel trip 4			50.2	0.51
BL Mean	45.6	0.49	44.5	0.57
SD		0.10		0.9
SD/mean %		0.21		0.16

TGA Analysis

TGA was used to determine the major components of PM collected on the filter papers from the single stage unit. The principle is to measure the sample weight loss during its heating in nitrogen to 550°C followed by air to 560°C. Water and VOF content were found in the 1st interval and carbon in the 2nd interval, with ash remaining

at the end of the test. The tests were carried out using the Shimadzu T50 (Japan) apparatus. The temperature programme and PM contents are illustrated for two example samples in Fig.3.

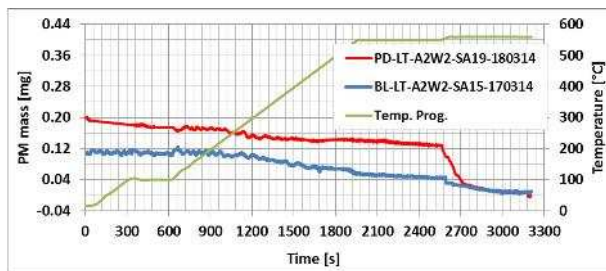


Fig. 3 TGA analyses for two samples taken from a fully loaded vehicle for PD and Ultra Biofuel (BL) blends.

It is clear that PM emissions from PD are higher than those of the blended fuel. A thorough comparison between the two graphs shows that the mass loss slope of the blended fuel is higher in the temperature range between 100-550°C which indicates a higher VOF content. A steep decrease in the PD curve at temperatures higher than 550°C, as air was introduced, indicates a higher proportion of EC from PD. TGA results averaged from 11 journeys are tabulated in Table 4.

Table 4 Average contributions of EC, VOF and ash to total PM concentration from TGA analyses and % variation when using blends compared to PD

PM component	Empty trailer			Loaded trailer		
	PD	BL	Variation	PD	BL	Variation
EC %	61.9	27.6	-74.0	61.5	30.5	-68.7
VOF %	25.0	57.8	34.9	27.7	60.7	38.0
Ash %	5.3	6.1	-33.2	3.4	3.0	-43.3
Total %			-41.6			-37.0

It can be inferred from Tables 2 and 4 that the blended Ultra Biofuel has the potential to reduce PM exhaust emissions when compared to PD, especially the EC component. This may be attributed to the lower carbon content in the C2G Ultra Biofuel (11% less carbon which reduces soot precursor formation) and higher oxygen content (12% more oxygen within the fuel for a complete combustion in the rich premixed zone and to increase OH radicals for soot burning at the diffusion flame zone). The stoichiometric AF ratio for C2G Ultra Biofuel is 12.17 compared to 14.48 for the PD. On the other hand the blended fuel has the propensity to produce more VOF than EC when compared to PD.

PM size segregated emissions

The two fuels exhibited different trends in particle size distribution as shown in Fig.4 by the average mass emissions over several journeys with PD vs the blended Ultra Biofuel. It is shown that most of the reduction of PM from the blended fuel is in the size range smaller than $PM_{2.5}$. The reduction in $PM_{2.5}$ concentration is 51.35%

and 73% for loaded and empty trailers respectively based on Table 5. This could be explained based on the fact that PM from PD is likely to be mostly ultrafine particles of soot within the nucleation and Aitken particle size modes which may be less likely to form large aggregates due to the relatively lower VOF emissions. Table 5 demonstrates the variation of blended fuel PM concentration for each size range with respect to PD. It is seen that most of the reduction is in the smaller size ranges. This may have beneficial consequences in terms of air quality impacts, since particles within these smaller size fractions penetrate more deeply into the human respiratory system, and are likely to have higher particle numbers per unit mass than larger particles.

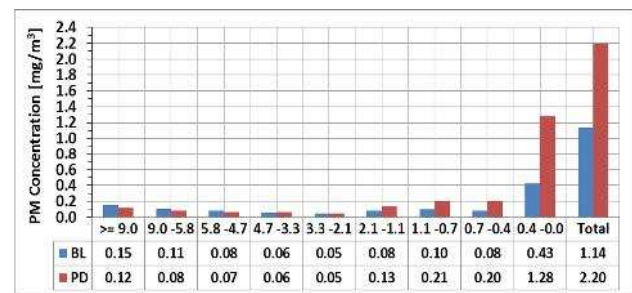


Fig. 4 PM size distribution based on averages across all journey samples for each fuel type: petroleum diesel (PD), C2G Ultra Biofuel blends (BL).

Table 5 PM concentrations for each size range for PD and blended fuels shown alongside the % variation in concentrations from the blended fuel with respect to PD (samples from Andersen Impactor).

PM size distribution	Empty trailer			Loaded trailer		
	PD mg/m³	BL mg/m³	Variation %	PD mg/m³	BL mg/m³	Variation %
>= 9.0	0.08	0.11	35.84	0.15	0.18	17.88
9.0 -5.8	0.06	0.09	40.26	0.10	0.12	20.35
5.8 -4.7	0.06	0.10	67.25	0.08	0.07	-4.64
4.7 -3.3	0.05	0.04	-28.71	0.07	0.07	-4.63
3.3 -2.1	0.05	0.03	-31.17	0.05	0.05	6.47
2.1 -1.1	0.14	0.07	-49.32	0.13	0.08	-33.49
1.1 -0.7	0.23	0.07	-71.23	0.18	0.12	-33.40
0.7 -0.4	0.22	0.06	-71.46	0.18	0.09	-52.61
0.4 -0.0	1.38	0.31	-77.33	1.17	0.49	-58.33
Total			-61.03			-39.85

Discussion and Conclusions

The study has shown that when using an on board fuel blending system, C2G Ultra Biofuel could be used safely as a surrogate for PD within a HDV under real world driving conditions. The high substitution ratios of C2G Ultra Biofuel that were achieved throughout the journeys led to lower total PM exhaust emissions when compared to the use of pure PD. Size distributed particulate analysis demonstrated that the reductions in PM mass were in the

smaller particle size fractions: less than 2.5 μ m diameter when based on D50% cut-off diameters used within the multi-stage Anderson Impactor. This is likely to imply reductions in soot emissions when using the biofuel blends, which is also supported by the lower EC content in the particle samples when using the blended biofuel. Since the use of the waste biofuel leads to avoided fossil fuel consumption, the tests demonstrate that when using an effective fuel blending strategy, Ultra Biofuel has the potential to reduce both lifecycle CO₂ and respirable particulate emissions leading to potential combined climate and air quality benefits.

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