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Emissions from a HGV using Used Cooking Oil as a Fuel under Real World Driving Conditions

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Abstract

To maximize CO2 reduction, refined straight used cooking oils were used as a fuel in Heavy Goods Vehicles (HGVs) in this research. The fuel is called C2G Ultra Biofuel (C2G: Convert to Green Ltd) and is a fully renewable fuel made as a diesel replacement from processed used cooking oil, used directly in diesel engines specifically modified for this purpose. This is part of a large demonstration project involving ten 44-tonne trucks using C2G Ultra Biofuel as a fuel to partially replace standard diesel fuels. A dual fuel tank containing both diesel and C2G Ultra Biofuel and an on-board fuel blending system-Bioltec system was installed on each vehicle, which is able to heat the C2G Ultra Biofuel and automatically determine the required blending ratio of diesel and C2G Ultra Biofuel according to fuel temperature and engine load. The engine was started with diesel and then switched to C2G Ultra Biofuel under appropriate conditions. Exhaust emissions were measured using PEMS (Portable Emission Measurement Systems) on one of the trucks under real world driving conditions. Comparisons of emissions between neat diesel mode and blended fuel mode were made. The results show that C2G Ultra Biofuel can reduce particulate matter (PM) and CO emissions significantly compared to the use of pure diesel.

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 CO2 emissions globally [1]. Road transport dominates total transport CO2 emissions. The UK Vehicle Certification Agency (VCA) reported that 90% of all transport GHG emissions were from road transport [1] . Heavy Duty Vehicles (HDVs), including HGVs and buses, are the second biggest source of carbon dioxide emissions, contributing about 25% of the emissions from the sector which is about 6% of the total EU emissions, with rail, international aviation and shipping all trailing it. The increasing traffic in road freight HGVs means that their CO2 emissions are still on the rise despite improvements in fuel efficiency over the last few years. This therefore calls for very urgent measures to tackle the high 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 [2].

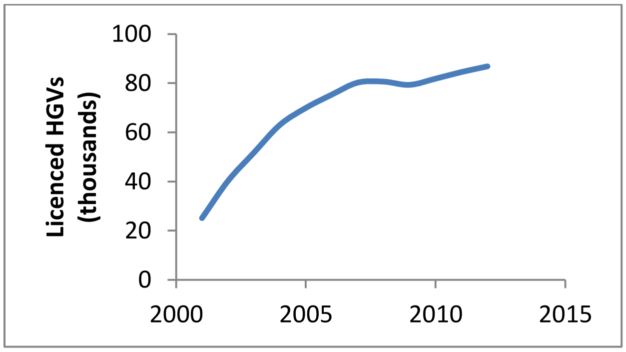

Figure 1: The trend for the number of HGVs (over 41 tonnes) in the UK

In the UK, the number of HGVs licensed during the period 1994-2012 exceeding 41 tonnes was 868,000, as shown in figure 1 (UK Department of Transport, 2013). It is assumed that each vehicle travels an approximate distance of 69,000 miles per annum (110,400 km annum) and covers 2.4 km per litre of fuel [3]. This would mean that on the basis of distance covered per annum, each truck consumes about 46000 litres of fuel each year. The carbon footprint from HGV is therefore significant.

Biofuels as a means to reduce the road transport carbon footprint 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) [4-10]. However, has the use of biodiesel delivered its main objective, that of-carbon reduction, and by how much compared to PD? The answer will vary. The potential for carbon reduction by biodiesels will depend on feedstock and production processes but the feedstock is a key parameter [11]. Currently biodiesels produced in the EU are mainly derived from edible vegetable oils as feedstock such as rape seed oil [12, 13]. These biodiesels (first generation) are often the topic of public debates due to their effects on rising food prices and ethical issues such as starvation in developing countries and the competition between land use for the cultivation of oilseeds as feed stocks for biodiesel manufacture, and land use for the cultivation of food crops. The second generation of biofuels for diesel engines uses non-edible biomass such as lignocellulose as the feedstock to produce synthetic diesel fuel, but the cost of the production process is high and not economically viable at present. Thus attention has been diverted to using Used/Waste Cooking Oil (UCO or WCO) as a feedstock to produce biodiesels [11, 14]. This offers easier acceptance by the public with regard to ethical issues and is more economically viable. It also contributes to sustainable waste management practices. In the UK, UCO's contribution to total biodiesel production reached 66% in 2012-13 [15].

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 [16] 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 [17] conducted a LCA (Life Cycle Analysis) assessment for a used cooking oil based biodiesel and found that the transesterification stage accounted for 68% of the total environmental impact. Li et al [18] assessed the carbon footprint of the used cooking derived biofuel tested in this paper and reported a 97% reduction in carbon emissions compared to diesel.

To maximize the carbon reduction potential of UCO, the EPID (Environmental and Performance Impact of Direct use of used cooking oil in trucks under real world driving condition) project has been set up to examine and investigate the environmental and performance impacts of the direct use of the refined straight used cooking oils (C2G Ultra Biofuel) in diesel engine powered 44 tonne trucks. Ten trucks in the United Biscuits Ltd distribution fleet have been converted to be able to burn the Ultra Biofuel with an on-board blending system-Bioltec system. A dual fuel tank containing the Ultra Biofuel and PD has been fitted to each truck. The Bioltec blending system is a microcomputer controlled automatic fuel selection and blending system, which can select fuel supply (PD or the Ultra Biofuel) and adjust the blending ratio based on certain measured engine operational parameters such as fuel temperature and load [19]. Fuel consumption, engine deposits, exhaust emissions, lube oil aging and operational performance have been monitored. This paper, as part of the project, assesses and compares emissions between the use of diesel and the C2G Ultra Biofuel under real world driving conditions.

The applications of SVO in diesel engines have been predominantly in the non-road diesel engine or agriculture sectors. 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 [20]. The heating of SVO is normally required to ensure proper fuel spray and mixing and to meet emission requirements. Several studies demonstrated that when SVO is heated up, a satisfactory combustion and emission performance could be achieved [21-23]. Another method to use SVO is to blend with diesel [24, 25]. Fontaras et al investigated emissions from passenger diesel cars using SVO-diesel blends over legislated and real world driving cycles [26]. 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, which meant that the impact of SVO on emissions will vary depending on driving cycles. Their results showed that in general SVO can reduce PM emissions but could increase hydrocarbon emissions. The CO emissions were increased by SVO in the NEDC cycle, but reduced in the other cycles. NOx (NO + NO2) emissions were at a similar level between SVO and neat petroleum diesel.

The studies on the emissions from using SVO in diesel engines carried out so far have been mainly conducted on engine test beds or small diesel vehicles. There are still gaps in knowledge on emissions from the direct use of neat vegetable oils in heavy duty trucks under real world driving. Hence, this paper aims to provide results on real world emissions from the direct use of refined used cooking oils (C2G Ultra Biofuel) under such conditions.

Experimental

Vehicles

The test vehicle is a GCW 44 tonne (GCW-Gross Combination Weight, the total weight of the tractor unit plus trailer plus full load) articulated truck. It is 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 axor C 2543) is powered by a DICI turbo-charged 6-cylinder in-line diesel engine (OM457.9). The engine capacity/displacement is 11.97 litres which develops a maximum output power of 315 kW@1900 rpm while the maximum torque is 2100 Nm@1100 rpm. The fuel injection system is unit injector type. A constant throttle and butterfly valve is used as an engine brake. In heavy duty vehicles, especially under heavy load conditions or vehicle moving downhill, it is not recommended to use the brake system for speed reduction as it might burn the friction discs or drums. Therefore the engine is used as a brake. This action is facilitated by cutting the air flow by a butterfly valve in the air passage.

The vehicle is fitted with a Selective Catalytic Reduction (SCR) after-treatment system for NOx reduction. Urea solution (Ad blue) is injected into the exhaust pipe at the engine outlet just after the turbocharger. This ensures the evaporation and complete mixing of the urea with exhaust gases due to the high exhaust temperatures and extended contact time. The SCR embraces the catalyst covered monolith to remove NOx. The downstream side of the monolith is covered with platinum to prevent NH3 slippage.

The tests were conducted for tractors with both empty and loaded trailers.

Fuels

A Standard petroleum diesel 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. It can be seen that 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. In this research, the C2G Ultra Biofuel was heated by the engine coolant water and the emission results showed that no adverse impacts due to fuel spray and mixing were observed. 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.

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

	The 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

Dual Fuel and On-board Fuel Blending System

A dual fuel tank with a split of 300 litres for biofuel or the C2G Ultra Biofuel and 160 litres for PD was retrofitted to trucks as shown in figure 2. A fuel-engine coolant heat exchanger was inserted to the biofuel tank side, which is part of an on-board fuel blending system-Bioltec 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 Bioltec fuel control module and heated further to 60-80 °C.

The Bioltec 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. Figure 2 shows the heated fuel tank of the Bioltec system. Figure 3 shows a schematic view of the map for the blending ratio control by the Bioltec system. T1, T2 and T3 represent the fuel temperatures. TGR is a relative engine load parameter. The vertical axis is the blending ratio. This map is individually configurable depending on the engine type, operational mode, fuel type and so on.

Figure 2: A dual fuel tank in a 44-tonne truck

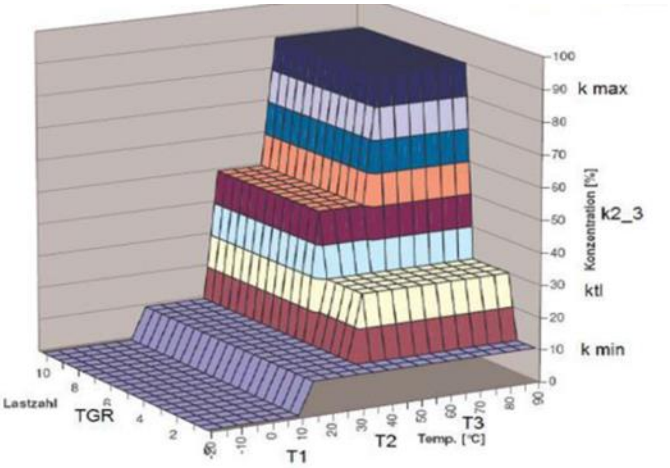

Figure **3**: Schematic view of blending ratio control map of the Bioltec system [19]

Exhaust Sampling Systems

Gaseous emission sampling systems

Exhaust samples were taken by three stainless steel probes with 6mm inside diameter inserted into the centre of the tailpipe by approximately 0.5 m upstream of the tail pipe exit: one for the gas sample and two for the PM samples (size segregated PM and single stage filter paper). The gas samples were transferred by a 5 meter long heated sample line (at 180 °C) to the FTIR system inside the cabin.

A portable Fourier Transform Infrared (FTIR) spectrometer was used to measure gaseous emissions. The model used was the Gasmet CR 2000 which is capable of measuring concentrations as low as 0.5-3 ppm, depending on the application. It has been specifically calibrated by the manufacturer to an accuracy of 2% within the calibrated measurement range, which was 20,000 ppm for CO and 30% for CO_2 respectively. The total hydrocarbon (THC) emission measurement was the sum of 38 selected hydrocarbon species that was calibrated by the manufacturer from 0~500 ppm individually (methane was calibrated to 1000 ppm) [27]. The FTIR measurement for regulated emissions was calibrated against standard CVS measurements by the authors using a chassis dynamometer facility and various driving cycles [28]. It was found that the FTIR measurement had excellent agreement with the CVS measurement for legislated emissions.

The vehicle has an OBD (On-Board Diagnostics) system to monitor NOx emissions along with other parameters. The malfunction Indicator Light (MIL) will be triggered if NOx exceeds a threshold that was set by the manufacturer in order to comply with emissions legislation. During the tests, the MIL was never on, indicating no exceedance of NOx emissions.

Particulate Matter (PM) sampling systems

PM samples were taken using two systems: a PM2.5 total mass measurement (Anderson Impactor 1) and size segregated measurements below PM10 using an 8 stage Anderson Impactor (Anderson Impactor 2). Figure 4 shows a picture of the sampling system set up in the cabin.

The PM2.5 total mass measurement utilized the pre-separator and backup stage of an Anderson Impactor to collect particles. The exhaust samples first travelled through an ice trap to remove water vapour and then passed through a PM2.5 cyclone to remove particles larger than 2.5 microns. The exhaust samples then entered the Anderson sampler (Anderson Impactor 1). The flow rate was controlled at around 16.7 L/min. Preconditioned glass fibre (GF/F) filter papers were used for PM2.5 collection.

PM samples for the size segregated analysis were taken by a stainless steel probe with 6mm inside diameter inserted into the centre of the exhaust pipe. The exhaust gas samples were transferred by a 3.6 m long with 6mm inside diameter insulated Teflon tube to an Anderson Impactor (Anderson Impactor 2) inside the cabin. The Anderson Impactor 2 consists 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). Table 2 shows 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. The sample flow rate was controlled at ~28.5 l/min to ensure proper size segregation of the particles within the manufacturers specifications. Within each stage there is a stainless steel collection plate on which the collecting substrate rests. The glass fibre filter papers were used as a substrate in this study to collect PM samples so as to enable further analysis in laboratory. Clean filter papers were conditioned in a desiccator for at least 24 hours before tests and weighed by a balance with an accuracy of 0.01 mg and then saved in the desiccator. After each test the loaded filter papers were saved individually in petri dishes and then wrapped in a plastic bag and kept in the fridge. When all the tests were finished, the loaded filter papers were placed into a desiccator for at least 24 hours and re-weighed. Blank filter papers also underwent the same procedure (apart from sampling) in order to estimate measurement errors. The Andersen Impactor 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.

Table 2: The stage number and the particle size ranges of the Andersen Impactor

Impactor stage	0	1	2	3	4	5	6	7	BF
PM size [μm]	≥9.0	9.0 - 5.8	5.8 - 4.7	4.7 - 3.3	3.3 - 2.1	2.1 - 1.1	1.1 - 0.7	0.7 - 0.4	≤0.4

NB: BF stands for Backup Filter.

Figure 4: On-board PM and gaseous sampling system

Test Trips and Procedures

The challenges associated with real world emission tests include the complexity of variables; including variations in traffic, driving behaviour, meteorological conditions, road geometry, vehicle load, vehicle condition etc. One of the main purposes of this paper is to compare the emissions between PD and C2G Ultra Biofuel. To minimize the effect of other parameters and reduce the complexity of the emission tests, the comparisons were made based on hot engine conditions and had the same Gross Vehicle Weight (GVW). The vehicle was driven by the same driver for all the tests. A fixed driving route was selected.

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 A roads and motorways. Hence, both low speed congested and high speed free flow travel under real world driving conditions can be represented. The journey started from Ashby De La Zouch and ended at Wigston and vice versa. The single trip distance is about 33 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). Figure 5 shows the driving route for all the tests. Figure 6 shows the vehicle road velocity, heading and elevation profile for a typical trip from Ashby to Wigston. The vehicle started from the UB distribution centre in Ashby and entered onto A511 road and then joined M1 motorway at

Junction 22 after travelling approximately 14 km. The journey on the motorway was approximately 12 km. The vehicle left the M1 at junction 21 and entered the A5460 then the A563 and finally arrived at the destination. The last part of the journey involved travelling through an urban area. The vehicle average velocity was 36-50 km/h for various runs.

The elevation profile in figure 6 shows that the whole journey (from Ashby to Wigston) can be roughly divided into an uphill section: 0-13km and a downhill section: 13-33km. The uphill section has an elevation of 30 m while the downhill section has an elevation of 50 m. The gradient is approximately 2.3 m/km for the uphill section and -2.5m/km for the downhill section respectively.

Figure 7 presents the design of the test program. The gaseous emissions were measured for each one way journey, i.e. Ashby to Wigston (A2W) or Wigston to Ashby (W2A). The size resolved PM concentration measurements were undertaken for each round trip because not enough PM mass could be collected on a one way trip.

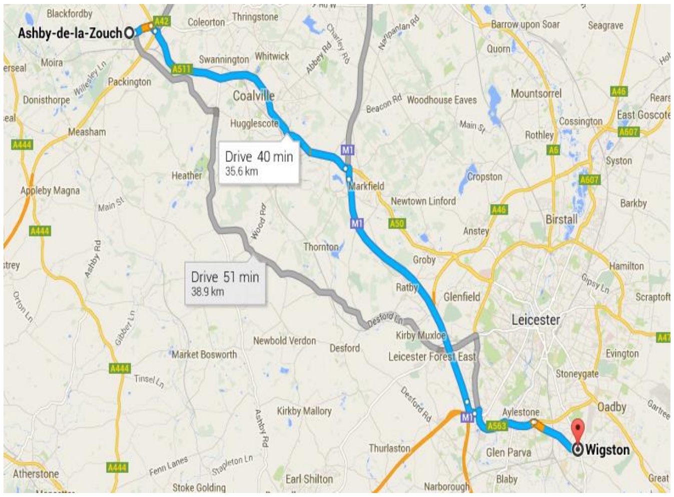

Figure 5: Map of the driving route for emission tests (Courtesy of Google Maps)

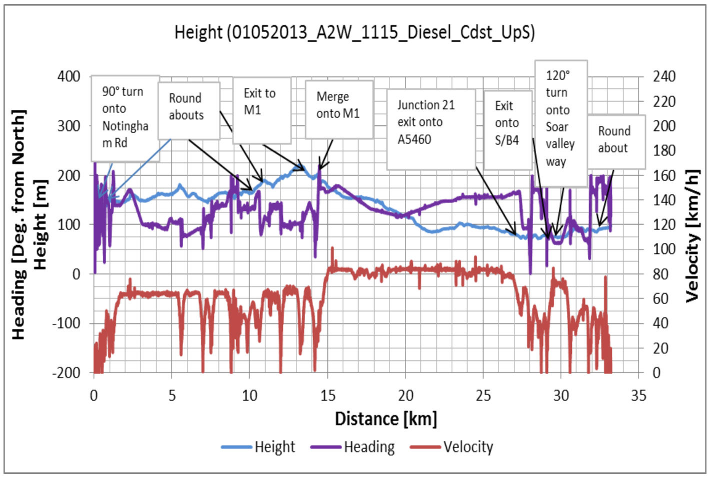

Figure 6: Profile of the vehicle velocity and elevation for a typical journey from Ashby to Wigston (A2W)

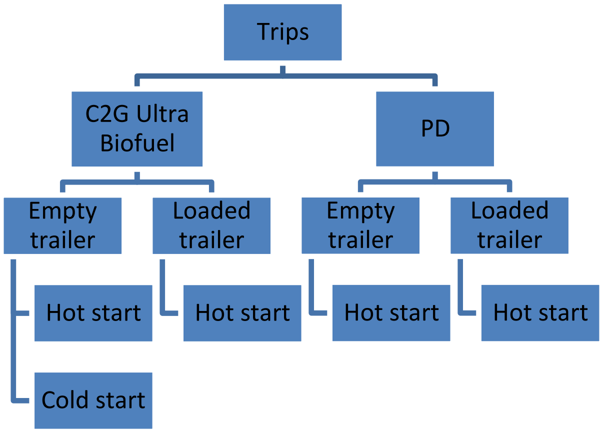

Figure 7: The test matrix

Results and Discussion

Transient Gaseous Emissions

CO emissions

Figure 8 shows the transient tailpipe CO emissions from PD as a function of time and vehicle velocity for two A2W trips with empty trailers (GVW ~16 tonnes). Figure 9 presents the tailpipe CO emissions for the blended fuel with similar GVW. The CO emissions from the four trips were generally low (concentrations were less than 10 ppm except spikes). There are some spikes in CO emissions which were mostly linked with accelerations. Though these four trips were run on hot engine conditions, there was an initial period of 500-600 s showing higher CO emissions. This is because the engine was switched off between testing trips for the removal of filter papers, zeroing of instruments and preparation for the next test. So the engine needed some time to reach a fully warmed up status.

By comparison of CO emissions between PD and blended fuel trips, it can be seen that the C2G Ultra Biofuel produced less and lower CO spikes.

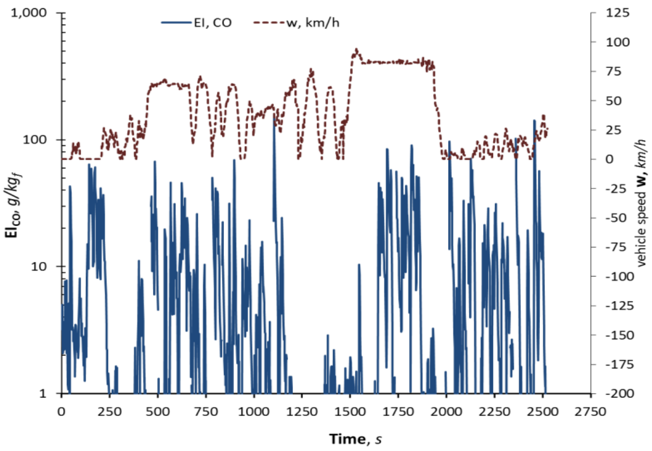

Figure 8: CO emission for an A2W trip (180314-1401) with an empty trailer in petroleum diesel driving mode

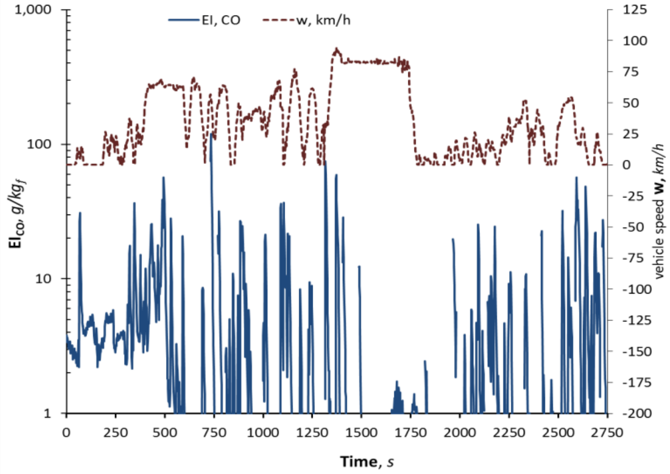

Figure 9: CO emission for an A2W trip (160314-1405) with an empty trailer in blended fuel driving mode

Hydrocarbon emissions

The hydrocarbon emissions are shown in figures 10 and 11 for PD and blended fuel modes respectively. It is surprising that there were no cold start hydrocarbon emissions which would be expected to be notably higher than that when the engine was fully warmed up, even when the engine was not starting from completely cold. This demonstrated that hydrocarbon emissions were not as sensitive as CO emissions to engine temperatures. Li et al [6, 29-32] investigated cold start emissions from SI passenger cars and a light duty diesel van and reported a greater increase in CO emissions than hydrocarbon emissions when the temperature of the engine in a vehicle was lower.

The hydrocarbon emissions showed very fluctuating profiles, which overshadowed the variation of hydrocarbon emissions with vehicular velocity. Nevertheless, general trends are that hydrocarbon emissions were not much changed along the trips.

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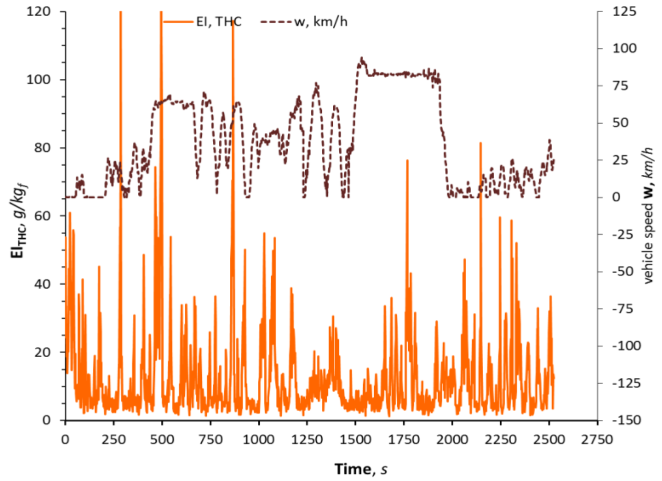


Figure 10: Hydrocarbon emissions for an A2W trip (180314-1401) with an empty trailer in petroleum diesel driving mode

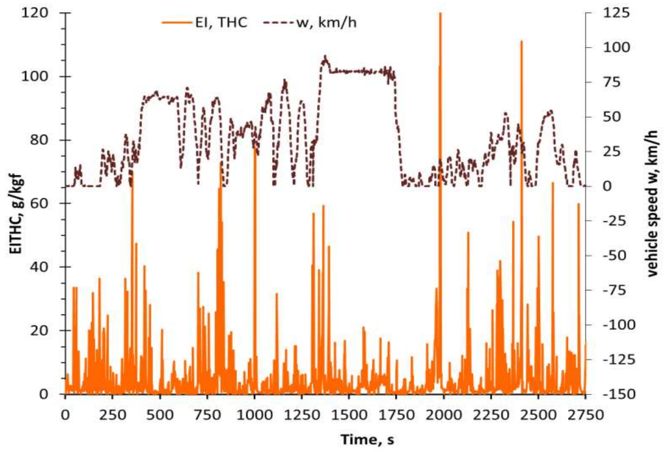


Figure 11: Hydrocarbon emissions for an A2W trip (160314-1405) with an empty trailer in blended fuel driving mode

Comparison of Trip Average Gaseous Emissions between PD and Blended Ultra Biofuel Trips

The substitution ratio of PD by the C2G Ultra Biofuel for these real world journeys has been investigated by the authors [33] with a reported trip average value of ~85%. Thus the emissions from blended fuel trips could be regarded as representative emissions from the C2G Ultra Biofuel. The trip average emissions were converted from ppm to emissions index (EI) (g/kg-fuel) for three diesel trips and two blended fuel trips for empty trailer tests as presented in table 3. Table 4 presents two diesel and three blended trips for loaded trailer tests. It can be seen that the CO emissions were reduced by half for the empty trailer tests and 25% for the loaded trailer tests respectively by the C2G Ultra Biofuel compared to diesel. This is likely to be due to the fuel borne oxygen which promotes the oxidation of fuel inside the combustion chamber. There was a slight reduction (6%) in hydrocarbon emissions by C2G Ultra Biofuel in the empty trailer tests. The reduction in hydrocarbons became more significant (21%) in the loaded trailer tests. This could be due to the fact that the increased combustion chamber temperature and fuel injection pressure at the higher engine load boosted the benefit of fuel born oxygen in the C2G Ultra Biofuel for the oxidation of fuel.

Table 3: Comparison of trip average emissions for empty trailer and hot start journeys

Trip number	Av speed (km/h)	CO (g/kgfuel)	THC (g/kgfuel)
PD trip 1	42.1	9.4	12.2
PD trip 2	51.3	11.9	17.5
PD trip 3	36.0	11.1	11.7
Mean	**43.1**	**10.8**	**13.8**
Standard Deviation (SD)	***7.7***	***1.3***	***3.2***
SD/mean %	***18.0***	***11.9***	***23.5***
Ultra Biofuel Blend trip 1	45.7	4.7	13.2
Ultra Biofuel Blend trip 2	49.5	5.1	12.8
Mean	**47.6**	**4.9**	**13.0**
Standard Deviation (SD)	***2.7***	***0.3***	***0.3***
SD/mean %	***5.7***	***6.3***	***2.2***
Reduction by the Ultra Biofuel (by mean) (%)		**54.6**	**5.8**

Table 4: Comparison of trip average emissions for loaded trailer and hot start journeys

Trip number	Av speed (km/h)	CO (g/kgfuel)	THC (g/kgfuel)
PD trip 1	42.7	5.8	12.2
PD trip 2	38.0	5.0	6.6
Mean	**40.3**	**5.4**	**9.4**
Standard Deviation (SD)	***3.3***	**0.6**	**4.0**
SD/mean %	***8.2***	***10.6***	***42.1***
Ultra Biofuel Blend trip 1	42.3	4.2	7.1
Ultra Biofuel Blend trip 2	39.8	4.5	8.2
Ultra Biofuel Blend trip 3	50.2	3.4	6.9
Mean	**44.1**	**4.0**	**7.4**
Standard Deviation (SD)	***5.4***	***0.5***	***0.7***
SD/mean %	***12.2***	***13.5***	***9.6***
Reduction by Ultra Biofuel (by mean) (%)		**25.1**	**21.3**

Particulate Matter (PM) Emissions

PM mass concentrations

Unlike the gaseous emissions which were analysed at 0.5 Hz, the PM emissions were taken collectively for each trip. This was because of a lack of reliable, transient and compact on-board PM emission instruments available. So the PM emissions were collected onto filter papers for each journey. One of the benefits for such methods is that the sample can be used for further chemical analysis.

Table 5 shows the $PM_{2.5}$ mass concentrations for petroleum diesel only and blended fuel tests with empty and loaded trailers respectively. Repeated trips were conducted. The results show that the C2G Ultra Biofuel can reduce PM emissions by 65~75%. The repeatability of the data was good, especially for the petroleum diesel empty trailer tests and loaded trailer blended fuel tests with a variation (SD/mean) of 11% and 16% respectively.

Table 5: Comparison of trip average emissions for $PM_{2.5}$ (mg/m^3) for diesel only 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	38	1.55
PD trip3	36	1.68	42.8	1.28
Mean	**43.13**	**1.92**	**41.17**	**1.62**
Standard Deviation (SD)	***7.70***	***0.21***	***2.74***	***0.37***
SD/mean %	***17.86***	***10.95***	***6.66***	***23.16***
Blended Fuel trip 1	45.7	0.42	42.3	0.49
Blended Fuel trip 2	49.5	0.56	39.8	0.69
Blended Fuel trip 3			50.2	0.51
Blended Fuel trip 4			45.6	0.6
Mean	**47.60**	**0.49**	**44.48**	**0.57**
Standard Deviation (SD)	***2.69***	***0.10***	***4.50***	***0.09***
SD/mean %	***5.64***	***20.20***	***10.11***	***16.03***
Reduction by Ultra Blended fuel (by mean) (%)		**74.4**		**64.6**

The significant reduction of PM by the C2G Ultra Biofuel is considered to be due to the fuel born oxygen, which assists the oxidation of the soot in the combustion chamber. The benefit of fuel born oxygen in the C2G Ultra Biofuel was also reflected by large reductions in the CO emissions (53%).

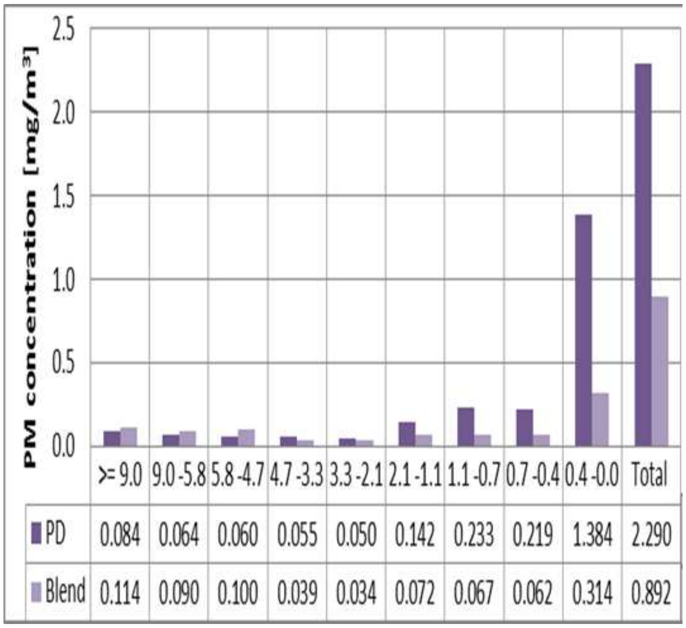
The PM emissions do not seem to be sensitive to engine load conditions, as reflected by comparisons between empty and loaded trailer tests. The difference in PM mass concentrations between the empty and loaded trailer tests is insignificant. The GVW is 16-20 tonnes for empty trailer and about 36 tonnes for loaded trailer trucks. It can be seen that doubled GVW for loaded vehicles produced similar PM emissions to that from unloaded vehicles.

PM size segregated emissions

Figure 12 shows the comparison of size resolved PM concentrations between the PD and blended fuel modes respectively for empty trailer trips measured by the Anderson Impactor 2. The trip average velocity was 40 to 50 km/h for the loaded trips, demonstrating similar vehicle movement behaviour. Although the average velocity of the journey alone could not be used to fully characterize the real world vehicle travel profile, it is one of the important driving parameters for travel profiles.

The results show that PM smaller than 2.1 micron is dominant, contributing 60-80% of the total PM mass concentration. The diesel trip produced significantly higher PM emissions than the blended fuel trip. Particulate mass emissions for the blended fuel trip were reduced by approximately 75% for particulates smaller than 2.1 microns. The total particulate mass from the empty trailer truck was reduced by ~60% for the blended fuel trip. This is in good agreement with the results in table 5.

The Authors investigated the blending ratio of the C2G Ultra Biofuel for these real world journeys and reported a substitution ratio of ~85%, which was fairly constant for all the hot start journeys [33]. So the PM emissions from the blended fuel trips were predominantly from the C2G Ultra Biofuel.

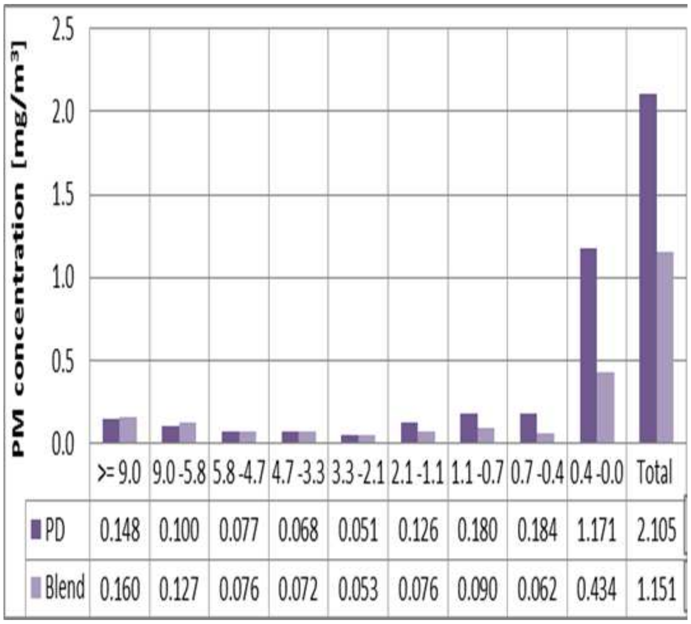


	>=9.0	9.0-5.8	5.8-4.7	4.7-3.3	3.3-2.1	2.1-1.1	1.1-0.7	0.7-0.4	0.4-0.0	Total
■ PD	0.084	0.064	0.060	0.055	0.050	0.142	0.233	0.219	1.384	2.290
■ Blend	0.114	0.090	0.100	0.039	0.034	0.072	0.067	0.062	0.314	0.892

Figure 12: Size resolved PM concentrations for petroleum diesel and blended fuel respectively for hot start trips with empty trailers

Figure 13 shows the comparison of size resolved PM concentrations between the PD and blended fuel modes respectively for loaded trailer trips. All the trips were started with hot engine conditions and had a GVW of ~36 tonnes. The trip average velocity was 42-44 km/h for all the trips, demonstrating very consistent travel profiles. Similar to the size resolved PM emissions from empty trailer trips, significant reductions by the C2G Ultra Biofuel were observed for the loaded vehicle tests. Particulate mass of the loaded truck were reduced by approximately 40-60% for particulates smaller than 2.1 microns for the blended fuel trip. The total particulate mass from the loaded truck for the blended fuel trip was reduced by ~45%.

As discussed earlier in the paper, the large reductions in PM emissions by the C2G Ultra Biofuel are considered to be due to the oxygen content in the C2G Ultra Biofuel, which helps the oxidation of soot during combustion. The absence of aromatics in the C2G Ultra Biofuel is also likely to help in reducing PM emissions. The viscosity of the C2G Ultra Biofuel is significantly higher than the PD, which may affect fuel spray. However, the results in this paper demonstrate that when coupled with an intelligent on board fuel blending and heating system, the high fuel injection pressures, small injector holes and advanced design of combustion chambers in modern diesel engines can overcome the higher viscosity effects of SVO (Straight Vegetable Oil) based biofuels such as C2G Ultra Biofuel and achieve satisfactory combustion and thus emission performance.



	>=9.0	9.0-5.8	5.8-4.7	4.7-3.3	3.3-2.1	2.1-1.1	1.1-0.7	0.7-0.4	0.4-0.0	Total
PD	0.148	0.100	0.077	0.068	0.051	0.126	0.180	0.184	1.171	2.105
Blend	0.160	0.127	0.076	0.072	0.053	0.076	0.090	0.062	0.434	1.151

Figure 13: Size resolved PM concentrations for petroleum diesel and blended fuel respectively for hot start trips with loaded trailers

Conclusions

Direct use of used cooking oil based biofuels in diesel engines without trans-esterification can deliver higher carbon reductions compared to its counterpart biodiesels. A 44 tonne articulated truck fitted with a duel fuel tank and an intelligent on-board fuel blending and heating device was used for emission tests. The Ultra Biofuel injection was controlled based on engine load and fuel temperatures. The exhaust emissions were compared between the use of neat petroleum diesel and the used cooking based biofuel (C2G Ultra Biofuel). The following conclusions are drawn:

1. The $PM_{2.5}$ mass measured by the single stage filter paper was reduced by 75% for the unloaded truck and 65% for the loaded truck respectively using the C2G Ultra Biofuel compared to PD. The total PM mass (PM_{10}) measured by the size segregated measurements showed a 60% reduction for unloaded truck tests and 45% reduction for loaded truck tests. The reductions in total PM_{10} were mainly focused on the ultrafine particles, i.e. smaller than 2.5 microns. 75% reductions for these ultrafine particles were observed on the unloaded truck and 40-60% reductions for the loaded truck were observed. The two PM measurements agreed well in terms of the % reductions.

2. CO emissions were reduced by ~50% for the empty trailer and 25% for the loaded trailer tests by the use of the C2G Ultra Biofuel, compared to PD.

3. There is a slight reduction in hydrocarbon emissions by the C2G Ultra Biofuel compared to diesel, though it is very variable.

4. The emission results demonstrated that there were no fuel/air mixing and combustion problems when the Ultra Biofuel was heated and its injection was properly controlled.

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Definitions/Abbreviations

CVS: Constant Volume Sampling

DfT: Department for Transport

DOC: Diesel Oxidation Catalyst

DPF: Diesel Particle Filter

FTIR: Fourier Transform Infra-Red

GCW: Gross Combination Weight

GVW: Gross Vehicle Weight

HDV: Heavy Duty Vehicle

HGV: Heavy goods Vehicle

NEDC: New European Driving Cycle

PD: Petroleum Diesel

PM: Particulate Matter

PPO: Pure Plant Oil

SCR: Selective Catalytic Reduction

C2G: Convert to Green

SVO: Straight Vegetable Oil

UCO: Used Cooking Oil

UB: United Biscuits Midland Distribution Centre

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