

Article

Emission Measurement of Buses Fueled with Biodiesel Blends during On-Road Testing

Séverine Cassiers ^{1,2}, François Boveroux ¹, Christophe Martin ^{3,4}, Rafael Maes ⁵, Kris Martens ⁶, Benjamin Bergmans ⁷, François Idczak ⁷, Hervé Jeanmart ² and Francesco Contino ^{2,*} 

¹ FLOW & BURN, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussel, Belgium; severine.cassiers@vub.be (S.C.); francois.boveroux@vub.be (F.B.)

² Institute of Mechanics, Materials and Civil Engineering iMMC, University of Louvain (UCLouvain), Place du Levant, 2, 1348 Louvain-la-Neuve, Belgium; herve.jeanmart@uclouvain.be

³ Walloon Regional Transport Company, SRWT-TEC, Avenue Gouverneur Bovesse 96, 5100 Namur, Belgium; christophe.MARTIN@letec.be

⁴ International Association of Public Transport, UITP, Rue Sainte Marie, 6, 1080 Brussels, Belgium

⁵ Hogere Zeevaartschool, HZS, Noordkasteel-Oost 6, 2030 Antwerpen, Belgium; info@hzs.be

⁶ Karel de Grote Hogeschool, KdG, Salesianenlaan 90, 2660 Hoboken, Belgium; kris.martens@kdg.be

⁷ Institut Scientifique du Service Public, ISSeP, Rue du Chéra 200, 4000 Liège, Belgium; b.bergmans@issep.be (B.B.); fr.idczak@issep.be (F.I.)

* Correspondence: francesco.contino@uclouvain.be

Received: 31 August 2020; Accepted: 25 September 2020; Published: 10 October 2020



Abstract: Increasing the biodiesel content of diesel fuels is encouraged because of its reduced carbon footprint. Pure rapeseed methyl ester (RME) and used cooking oil methyl ester (UCOME) are characterised by well-to-tank greenhouse gas (GHG) reductions of 54% and 88% compared to pure B0 petrodiesel, respectively. Captive fleets such as public transport buses could benefit from these GHG reductions by increasing the biodiesel content of their fuel because they have a consequent yearly fuel consumption. The aim of this paper is to compare on-road tailpipe emissions of a diesel bus when increasing the biodiesel concentration in the fuel. The tests were carried out on a standard city bus belonging to the Euro V EEV emission standard that was equipped with a portable emission measurement system measuring NO, NO₂, PN, CO and CO₂ at the tailpipe. The bus followed the SORT which is representative of urban bus driving. The heavy urban on-road measurements indicated increased NO_x emissions (24–26%), decreased PN emissions (43–45%) and slightly decreasing CO emissions for B30 RME and UCOME compared to B7. A measurement uncertainty analysis showed that the CO emissions were less reliable. Similar conclusions were drawn for the easy urban on-road bus emission measurements with smaller differences between B7 and B30 RME and UCOME.

Keywords: biodiesel; PEMS; RME; SORT; transit bus; UCOME

1. Introduction

Biodiesel has a positive impact on CO₂ emissions with an estimated overall greenhouse gas (GHG) reduction of 30% to 90% compared to diesel depending on the type of biodiesel [1]. Provided that it is produced with effective processes and sustainable life-cycles (e.g., using domestic biomass) [2–5], biodiesel could contribute to the energy transition effort. In Western Europe, the diesel fuel used for vehicles and available at fuel stations may contain up to 7 vol.% of biodiesel. Increasing the volume concentration of biodiesel would reduce the carbon footprint of the fuel used by vehicles.

Captive fleets such as long-haul trucks and transit buses would in particular benefit from large scale GHG reductions when using a fuel with higher biodiesel concentration. These fleets are characterised by predictable and recurrent driving and refuelling patterns thus involving

substantial annual fuel consumptions. For public transport buses, an annual mileage of more than 300 Mio kilometres has been recorded in Belgium in 2018 [6–8]. In the transition towards greater electrification, biofuels could help reduce the carbon footprint of current bus fleets whose average service life varies between 10 and 15 years [6,7]. However, this should not be at the expense of an increase in other emissions including noxious local pollutants such as nitrogen oxides and particulate matter.

Due to the high viscosity of biodiesel compared to diesel, combustion of pure biodiesel in engines may encounter issues such as poor fuel atomization and slow fuel flow at low temperatures [9]. Alternatives such as microemulsions have been proposed in other studies [10–14]. Several heavy-duty engine manufacturers allow the use of fuels concentrated up to 30 vol.% in biodiesel (B30) without requiring any modification. The transition from B7 to B30 fuels on buses is thus a possible alternative that reduces considerably the fleet's carbon footprint without modifications of the actual bus fleet. The carbon footprint of B30 rapeseed methyl ester (RME) and B30 used cooking oil methyl ester (UCOME) is reduced by 12.4% and 24.8%, respectively, compared to B7 RME (see Section 2.1).

The effects of biodiesel on emission performances have mainly been studied in the literature during laboratory engine dynamometer tests without aftertreatment systems and often at steady state operating conditions [9,15–17]. The impact on tailpipe emissions in real driving conditions is poorly quantified on heavy-duty vehicles for biofuels in higher concentration such as B30 [17]. It is of utmost importance to perform on-road emission measurements in representative real-driving conditions in order to be as close as possible to real-world emissions. Homologation requires to test the emissions of heavy-duty vehicles following the worldwide harmonized heavy duty (WWHD) test cycle on an engine dynamometer. However, these tests are not representative of the real use of the engine in operation whose application could vary between long haul trucks and public transportation buses.

The U.S. Environmental Protection Agency conducted an extensive review on the effects of biodiesel blended fuels (soybean, rapeseed or animal biodiesel) on emissions of pollutants of heavy-duty highway engines of 1997 and earlier [18]. They concluded that the emissions impacts of biodiesel did not differ by engine model year. A comparison with emissions impacts collected from non-road engines and light-duty vehicles did not allow for concluding that different engine groups respond in the same way as heavy-duty engines do. This highlights the importance to study the emissions impacts of biodiesel on heavy-duty buses specifically. They did not observe a significant difference in exhaust CO₂ emissions between biodiesel and conventional diesel. The average emission impacts of biodiesel (B30) for heavy-duty highway engines indicated an increase in NO_x emissions of ~5% and a decrease in PM, CO and HC emissions of ~18%, ~18% and ~29%, respectively. However, this database did not contain any engine equipped with exhaust gas recirculation (EGR), NO_x adsorbers or PM traps. Moreover, it only considered emissions measurements performed on engine dynamometers following the composite FTP, hot-start FTP and European emission test for type approval of HD engines (UN/ECE R49).

Anderson et al. [19] studied the effects of biodiesel fuels use on vehicle emissions of HD vehicles and had different conclusions for the emissions of on-road testing and chassis dynamometer testing. NO_x emissions were significantly higher for B20 and B100 as opposed to B0 for the HD dynamometer but did not differ significantly for the HD on-road emissions testing. In addition, a significant decrease in fuel economy was noticed for B20 as opposed to B0 in the HD dynamometer tests which was not measured during the HD on-road tests.

Another review by Hoekman et al. [20] gathered emissions performances on HD and LD engine and chassis dynamometers fueled with biodiesel under transient and steady-state conditions. From the analysis of nearly 100 literature references, they obtained average predicted changes in emissions of −0.6% for NO_x, −18.7% for CO, −21.2% for HC and −24.1% for PM when the HD engines were fueled with B20 as opposed to B0. Like the review of the U.S. Environmental Protection Agency [18], their study showed large differences in biodiesel emission impacts between LD and HD tests.

Rajaeifar et al. [17] highlighted the lack of reliable emissions measurements of urban buses fueled with biodiesel blends under real-world operating conditions in the literature. More specifically, a clear need for careful and complete experimental designs is identified taking into account covariate factors such as ambient conditions. In addition, Rajaeifar et al. [17] also noticed a lack of statistical analysis of the emission measurements. As an example, Merkisz et al. [21] compared emission measurements on a 18m bus fueled with pure diesel and B100 RME during standardised on-road test cycle (SORT) but did not include measurement uncertainties. This paper addresses these shortcomings by post-processing raw emission measurements with correction factors that take into account the ambient weather conditions. The innovative scientific contribution of this paper is to perform on-road emission measurements with a portable emission measurement system (PEMS) following representative conditions of urban bus driving. The real impact on emissions of biodiesel compared to diesel is thus quantified as opposed to the homologation engine dynamometer emission measurements.

2. Methods

This section first presents the fuel blends used during the experiments and then provide the details of the on-road tests.

2.1. Biodiesel Blends

The on-road test compares the emission performances of two B30 biofuels composed of 30 vol.% of either RME or UCOME with B7 fuel available at fuel stations. The latter is composed of 6.5 vol.% and 6.7 vol.% of Fatty Acid Methyl Esther (FAME) which may contain RME. The B7 fuel is used by public transportation companies for their diesel buses in Belgium. All fuels tested in this study are compliant with the EN590 and EN14214 norms. The sustainability of the renewable fuel supply chain is ensured by the international sustainability and carbon certification (ISCC) and the biomass biofuel sustainability scheme (2BS), both certifications defined by the European Commission. In addition, the biodiesel is compliant with the US Environmental Protection Agency [22].

RME is produced from vegetable oil by transesterification which currently provides the highest conversion efficiency at the lowest cost [17]. The Renewable Energy Directive II 2018/2001/EC promotes biofuels and biogas produced from used cooking oil for transport. Their energy content may be considered doubled in the target of reaching a 14% renewable energy share within the final consumption of energy in the transport sector by 2030. The Renewable Energy Directive II 2018/2001/EC defines an estimate of the GHG emission savings and total GHG emissions of biofuels for their cultivation, processing, transport and distribution and that are representative of the European Union consumption. Table 1 summarises these GHG emissions of rapeseed biodiesel and used cooking biodiesel of varying concentrations when produced with no net carbon emissions from land-use change [1]. A transition from B7 RME to B30 RME could already reduce the well-to-tank (WTT) GHG emissions by more than 10 gCO_{2eq}/MJ which corresponds to a 14% reduction.

Table 1. The GHG emissions for the cultivation, processing, transport and distribution of biofuels decrease as the volume concentration of RME increases. The reduction in WTT GHG emissions when shifting from pure fossil diesel (B0) to pure RME biodiesel (B100) or to pure UCOME biodiesel (B100) is 52% and 88%, respectively [1].

	GHG Emissions [gCO _{2eq} /MJ]	GHG Reduction Compared to B0 [%]
B7 Rape seed biodiesel	91.3	3.6
B30 Rape seed biodiesel	80.0	15.6
B30 Waste cooking oil biodiesel	68.7	26.4
B100 Rape seed biodiesel	45.5	52
B100 Waste cooking oil biodiesel	11.2	88

The composition and specifications of the B30 RME and B30 UCOME samples indicate only small differences between both fuels (Table 2). For both fuels, the carbon, hydrogen and oxygen content amounts to 83.5 molar %, 13.7 molar % and 2.84–2.85 molar %, respectively. The hydrogen and carbon atomic ratio were measured with the ASTM D5291 method and the oxygen atomic content was calculated based on the two previously mentioned atomic ratios. These values were measured on B30 RME and B30 UCOME samples that were produced in the same way at the same refinery as the samples used in the presented tests.

Table 2. The specifications of the B30 RME and B30 UCOME samples indicate only small differences between both fuels. The composition and heat of combustion were measured on B30 RME and B30 UCOME samples that were produced in the same way at the same refinery as the samples used in the presented tests.

	Method	Unit	B30 RME	B30 UCOME
Carbon content	ASTM D5291	molar %	83.5	83.5
Hydrogen content	ASTM D5291	molar %	13.65	13.66
Oxygen content	Calculated	molar %	2.85	2.84
Nitrogen content	ASTM D4629	mg/kg	20	19
Sulfur content (UVF)	EN ISO 20846	mg/kg	5.9	7.3
Net Heat of Combustion	ASTM D240	MJ/kg	41.320	41.314

2.2. On-Road Testing

2.2.1. Experimental Design: Bus and On-Road Test Cycle

We performed on-road emission measurements on a 12 m diesel city bus. The tested bus is representative of the Western European bus fleets and has already covered nearly 400,000 km for TEC, one of the Belgian public transportation companies. The bus belongs to the Euro V EEV emission standard and has SCR and DPF aftertreatment systems. Technical specifications of the tested bus are detailed in Table 3. The empty weight of the vehicle amounts to 11,050 kg and the load present in the bus during the tests is estimated to 400 kg including the three people on the bus during the test, the emission measurement equipment, the secured driver cabin, and ticketing equipment.

Table 3. A 12 meter diesel bus matching the Euro V EEV emission standard is tested under actual vehicle operating conditions. This bus has SCR and DPF aftertreatment systems reducing NO_x and particulate matter emissions, respectively.

Engine Type	CI, 4-Stroke
Displacement	9 186 cm ³
Number of cylinders	6, in line
Maximum power	228 kW at 2 200 rpm
Maximum torque	1 275 Nm at 1 700 rpm
Gearbox type	Automatic
Emission standard	Euro V EEV
Year of registration	2011
Mileage	396,592 km
Empty weight	11,050 kg

Emissions are measured following the SORT in order to compare in a reproducible way the emissions of the different fuels during typical driving patterns of transit buses in operation. These on-road test cycles have been defined by the UITP Bus Committee based on more than 10 million kilometres of operation data of transit buses and represent typical stop-and-go operation of a scheduled service bus as opposed to the engine tests required for vehicle certification [23]. The main aim of SORT is to have a reproducible comparison in fuel consumption of buses. These on-road test cycles have been

defined since 2004 when real-operation on-road emission measurements with a PEMS were not yet required for in-service conformity tests. SORT is thus a precursor for on-road test cycles representative of buses' real operation.

The heavy urban SORT 1 and easy urban SORT 2 are selected for the measurement campaign given their higher impact on local air pollution than the suburban SORT 3. Urban operation covers more densely populated areas and is moreover characterised by a lower commercial speed. At average speeds lower than approximately 30 km/h, the fuel consumption of a bus increases as the commercial speed decreases [23]. The rated average speeds of base cycle SORT 1 is 12.1 km/h and SORT 2 is 18 km/h. SORT 1 and 2 are each composed of three simple trapezoidal speed profiles defined by an acceleration, a section at constant speed and a deceleration. It then ends with a stop, keeping the engine at idle (see Figure 1). More accurate specifications of the on-road test cycles are detailed in Table 4.

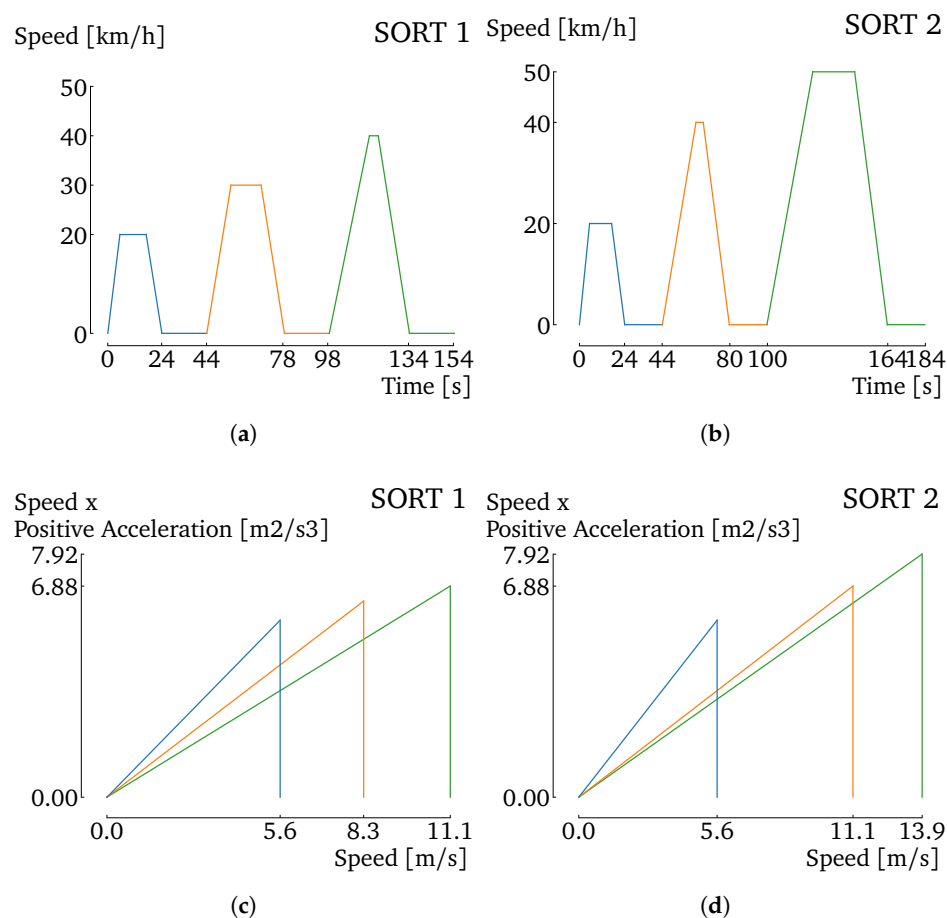


Figure 1. Each SORT base cycle 1 (a; c); and 2 (b,d) is composed of three trapezoidal speed profiles defined by an acceleration, a section at constant speed, a deceleration, and an idling period. The speed increase is sharper for the first trapezoid than the following ones.

Table 4. Specifications of the two base cycles SORT 1 and 2 that are representative of heavy and easy urban driving with average speeds of 12.1 km/h and 18 km/h respectively.

	SORT 1	SORT 2
Commercial speed [km/h]	12.1	18
Stop time [%]	39.7	33.4
Stop duration [s]	20	20
Total distance [m]	520	920
Acceleration trapeze 1 [m/s^2]	1.03	1.03
Acceleration trapeze 2 [m/s^2]	0.77	0.62
Acceleration trapeze 3 [m/s^2]	0.62	0.57
Deceleration all trapezes [m/s^2]	0.8	0.8

Although SORT is a standardised cycle and is not represented in full in real-world conditions, it is approaching real-world conditions since the test cycle is performed on the whole vehicle on the road instead of on an engine dynamometer as required for type approval. In addition, the test cycle is defined based on statistically generated data from several European transport companies (commercial speed, average time spent at stops, average distance between them, load, etc.) [23].

The load imposed by the SORT methodology for this particular bus in order to reach half load amounts to 3668 kg. A lack of space did not allow for adding in practice an additional load of 3.2 tons inside the bus given that the PEMS had to be accessible during the tests to verify regularly that no warning or errors were shown and took 10 seats in the back of the bus. However, the stiffer accelerations performed during the tests compared to the SORT cycle (see supra) can compensate the absence of load. Finally, given that all the tests were performed with an identical load, a comparison of the emissions of the different fuels can be done.

2.2.2. Portable Emission Measurement System

A PEMS by AVL is used for the on-road emission measurements. The PEMS consists of the following devices that are all connected to the AVL M.O.V.E. control system:

- *The AVL Gas PEMS iS* which is composed of NDIR and NDUV gas analysers for measuring carbon oxides (CO , CO_2) and nitrogen oxides (NO , NO_2), respectively.
- *The AVL PN PEMS iS* which consists of the modified particle detector Partector from Naneos working by DC. The PN counter is preceded by a VPR that is composed of a two stage dilution with an evaporation tube and catalytic stripper ($300\text{ }^\circ\text{C}$) between the primary and secondary dilution [24]. The VPR is connected to the tailpipe with a short heated line ($\leq 1\text{ m}$) at $150\text{ }^\circ\text{C}$ to avoid corrosion and the condensation of NO_2 and hydrocarbons.
- *The AVL EFM* which gives a direct measurement of the instantaneous exhaust flow rate by using a pressure differential device (pitot tube). The EFM has a pipe size of four inches and measures flow rates between 30 kg/h and 2140 kg/h at $100\text{ }^\circ\text{C}$.
- *The Dearborn Protocol Adapter DPA 5 of DG Technologies* which allows for record engine parameters such as the engine temperature and the vehicle and engine speeds via the OBD interface.
- *A Garmin GPS* which provides vehicle localization, altitude, and ground speed.
- *An ambient sensor* measuring ambient temperature and relative humidity.

The tailpipe on the top of the bus is extended with the EFM to which a sampling probe is connected (Figure 2). A heated line brings the sample exhaust gases through the roof trapdoor of the bus to the emission analysers inside the bus. The GPS and ambient sensor are installed on the roof of the bus.



Figure 2. The emissions are measured at the tailpipe of the bus. A sampling probe is installed after the EFM, before guiding the exhaust gases towards the back of the bus.

Post-processing calculations were performed with the AVL CONCERTO M.O.V.E. software according to the ISO16183 standard. A time alignment is firstly performed between the following signals:

- the GPS and ECU velocity
- the ECU throttle position and CO₂ measurement
- the CO₂ measurement and exhaust mass flow measurement
- the ECU throttle position and particle number measurement

During the pre and post tests, zero and span adjustments of the gas analysers are performed with calibration gases. The measured concentrations are corrected for drift in the post processing according to the European Regulation EU R49 [25]. Drift-corrected raw exhaust gases are thereafter converted to wet concentrations. This results in comparable absolute measurements with the same content of water. The drift-corrected raw exhaust gases are hence multiplied with the dry-to-wet correction factor of the ISO16183 standard which is a function of the dry CO and CO₂ concentration of the exhaust gases and the absolute humidity (Appendix A). For the emission measurements, the dry-to-wet correction factor varied between 0.883 and 0.996. For NO_x emissions only, an additional correction factor is applied to take into account the ambient conditions since a higher water content in the intake air reduces the formation of NO_x during in-cylinder combustion [26]. The NO_x correction factor for ambient conditions of the ISO16183 standard for compression-ignition engines is a function of the absolute humidity and the ambient temperature (Appendix B). For the emission measurements, the NO_x correction factor for ambient conditions varied between 0.941 and 1.017. Instantaneous mass emissions are computed for each pollutant according to the EU legislation by multiplying the instantaneous concentration of the component in the exhaust gas with the instantaneous exhaust mass flow and a tabulated component specific factor. The latter one is the ratio between the density of the exhaust component and the density of the exhaust gas. The following equations detail the mass emission rate calculations:

$$\dot{m}_{\text{gas}} = X_{\text{gas, DC}} \text{CF}_{\text{dry/wet}} \dot{m}_{\text{exh}} u_{\text{gas}} \quad (1)$$

$$\dot{m}_{\text{NOx}} = X_{\text{NOx, DC}} \text{CF}_{\text{dry/wet}} \text{CF}_{\text{NOx}} \dot{m}_{\text{exh}} u_{\text{NOx}} \quad (2)$$

where $\dot{m}_{\text{gas}}$ is the mass flow rate of the measured gas (g/s), $X_{\text{gas, DC}}$ is the drift-corrected fraction of gas measured by the PEMS (ppm or %), $\text{CF}_{\text{dry/wet}}$ is the dry-to-wet correction factor (-), $\dot{m}_{\text{exh}}$ is the exhaust mass flow rate (kg/s), u_{gas} is the component specific factor (-) and CF_{NOx} is the NO_x correction factor for ambient conditions (-).

The distance-specific emission E_{gkm} of one SORT cycle is computed as follows:

$$E_{\text{gkm, gas}} = \frac{\sum_i \dot{m}_{\text{gas, i}} (f_{\dot{m}})^{-1}}{d_{\text{ecu}}} \quad (3)$$

where $f_{\dot{m}}$ is the sampling frequency of the mass flow rate and d_{ecu} is the distance of a SORT repetition computed from the ECU vehicle velocity.

For particle number emissions, no correction factor is applied in the post-processing because the amount of particles present in the exhaust gases is not influenced by the varying concentration of gases including water. The VPR and heating lines ensure that only non-volatile components are entering the PN measurement device.

2.2.3. Uncertainty Quantification

The physical quantity E_{gkm} of the measured gas emissions involves combined uncertainties because it is computed from the following 6 (or 7 for NOx emissions) measured quantities:

- $X_{gas, DC}$, drift-corrected fraction of gas measured by the PEMS,
- $\dot{m}_{exh}$, the exhaust mass flow rate,
- $X_{CO, DC}$ and $X_{CO_2, DC}$, the drift-corrected fraction of CO and CO₂ measured by the PEMS,
- H_a , the absolute humidity,
- d_{ecu} , the trip distance computed from the ECU vehicle speed,
- T_{amb} , the ambient temperature (for NOx emissions only).

Considering that these 6 (or 7 for NOx emissions) measurements are uncorrelated and that the second order derivative factor is negligible, the global uncertainty of the physical quantity $E_{gkm} = f(W_1, \dots, W_{6/7})$ is expressed with Equation (4) [27]. A normal distribution is considered for the rate of emission per kilometre E_{gkm} of one SORT cycle. The maximum uncertainty of E_{gkm} with a 95% probability is thus computed as follows:

$$u_Z = \sqrt{\sum_{i=1}^{i=6/7} \left(\frac{\partial f}{\partial W_i} \right)^2 u_{W_i}^2} \quad (4)$$

$$u_{95,Z} = 1.96 * u_Z \quad (5)$$

Only the accuracy is considered for the uncertainties of the emission measurements because the linearity, repeatability and span and zero drift of the gas analysers are much smaller [28–30]. Table 5 lists the accuracy of the measurement devices.

Table 5. The accuracy of the gas analysers and the EFM is small compared to the experimental variability and does not exceed 2.5% of the analysers' measurement range. The linearity, repeatability and span and zero drift of the gas analysers is neglected in this uncertainty quantification [28–30].

	Accuracy	Measurement Range
EFM	±2.5% of reading or ±0.5% F.S.	30–2 140 kg/h at 100 °C
NDIR CO	±30 ppm abs. ±2% rel.	0–1 499 ppm 1 500–49,999 ppm
NDIR CO ₂	±0.06 vol.% abs. ±0.5% F.S.	0–9.99 vol.% 10–20 vol.%
NDUV NO	±2% rel. or ±0.2% F.S.	0–5 000 ppm
NDUV NO ₂	±2% rel. or ±0.2% F.S.	0–2 500 ppm

The RDE Commission Regulation 2016/427 imposes a maximum deviation of 4% for the total trip distance calculated from the ECU vehicle speed between the measurement instrument and the distance as calculated with a topographic map. Hence, a conservative and worst case accuracy of 4% is taken into account for the trip distance computed from the ECU vehicle speed. An accuracy of ±0.4 °C and 4% of the measurement is considered for the ambient temperature measurement and the absolute humidity, respectively [31].

The maximum uncertainty with 95% probability computed for the SORT 1 and 2 test runs with B7, B30 RME, and B30 UCOME are 10.7 g/km for CO₂ and 0.14 g/km for NOx. This measurement uncertainty does not take into account the variance of the measured emissions which will be highlighted on the graphical representation.

For the particle number emissions, the measurement uncertainty of the particle detector Partector is predominant indicating an accuracy of $\pm 1000 \text{ \#/cm}^3$ or $\pm 30\%$ of the measurement range ($0\text{--}10^6 \text{ \#/cm}^3$), whichever is greater. As simplification, we consider a conservative accuracy of $\pm 30\%$ of the particle number emission rate per kilometre.

2.2.4. Quality Assurance: Trip Validity SORT

The repetitions of the experimental SORT cycles are compared with the SORT cycle guideline by firstly verifying the speed profile per unit of distance (Figure 3). The velocity profiles of the repetitions slightly deviate from the theoretical SORT guideline, but the different test runs show a good reproducibility. The more severe accelerations of the experimental test runs are responsible for shorter acceleration periods and earlier idling times than the SORT guideline because the target velocity of the speed trapeze is reached earlier. The idling times are defined by the 20-s periods where the bus is stopped with the engine running and during which the doors are opened and closed as required by the SORT cycle. The graphs in the results section below will indicate acceleration times at 0 s, 44 s, 100 s and idling periods at 22–42 s, 73–93 s, 120–140 s and 22–42 s, 73–93 s, and 147–167 s for SORT 1 and 2, respectively.

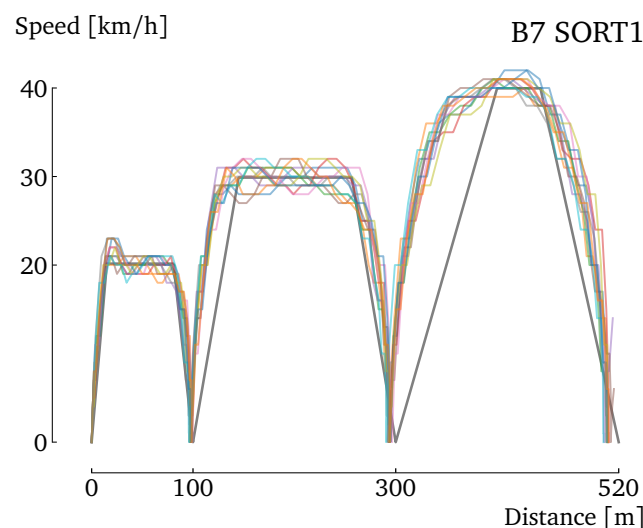


Figure 3. The velocity profile of the repetitions (individual lines on the figure) is close to the theoretical SORT guideline except for deviations at the nonlinear velocity changes of the guideline.

Figure 4 compares the velocity times positive acceleration of the experimental cycles with the SORT guideline for different velocities. The coordinates on the graph represent the instantaneous measurement (1 Hz) of velocity and acceleration during SORT 1 repetitions. A deviation is again observed from the theoretical SORT guideline; it is conservative because it covers a more aggressive area of acceleration than the guideline. A SORT repetition is valid when the speed profile is outside of the trapezoidal speed profile which is conservative. Moreover, the stiffer accelerations of the repetitions compared to the SORT guideline partly counter-balance the lack of load that is required inside the bus by the SORT and not reached in practice (see Section 2.2.1).

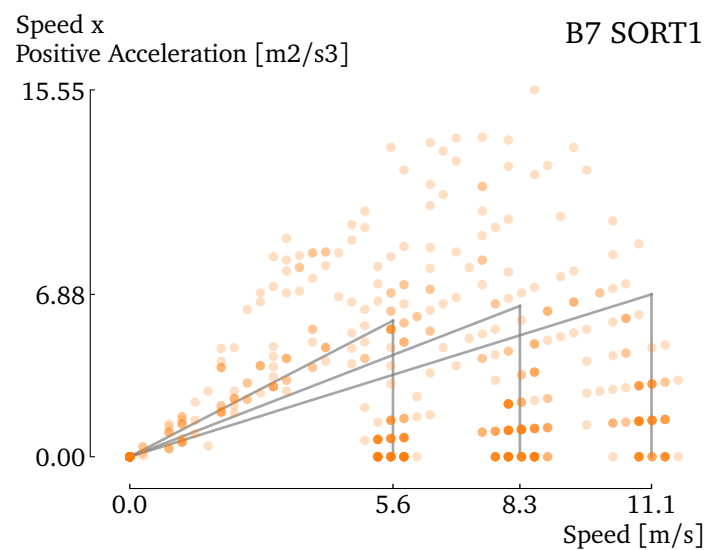


Figure 4. The instantaneous velocity times positive acceleration of the repetitions cover a more aggressive region of the SORT guideline leading to conservative results.

Lastly, a comparison of the emission measurements of the different test runs shows that the differences between test runs regarding driving patterns does not largely affect the emission measurements (Figure 5). During accelerations, large increases in NOx emissions are observed and idling periods are characterised by the same stabilised emissions for different test runs. The cumulative NOx emissions show the good reproducibility of the SORT 1 test runs with

The velocity profiles and dynamics of the driving patterns as well as the emission measurements of the different test runs show good reproducibility, validating a comparative analysis of the different fuels.

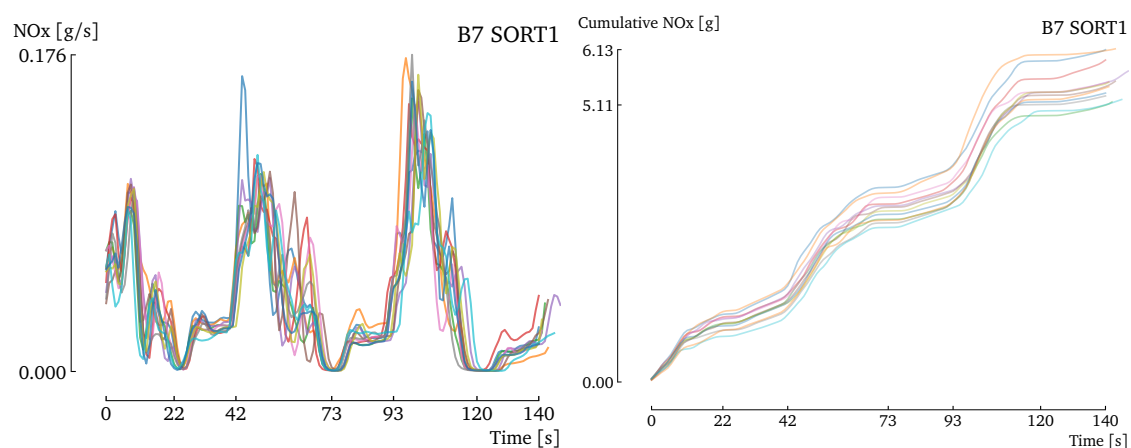


Figure 5. The NOx emission rate of the different SORT 1 runs (individual lines on the figure) are characterised by large increases during accelerations and stabilised low NOx emissions during idling. The cumulative NOx emissions measured during the different SORT 1 runs shows a good reproducibility.

3. Results and Discussion

During the heavy urban SORT 1 cycle, increased nitrogen oxide emissions are measured when the bus is fueled with B30 RME and B30 UCOME compared to B7. In Figure 6, each point represents the NOx distance specific emission measured during one SORT 1 cycle repetition. A swarm plot is selected for representing the measurements in order to show the spread of the repetitions and the overlapping

points clearly. The increase in NO_x emissions is due to the higher oxygen content of biodiesel compared to petrodiesel, thus promoting the combustion and heat release rate. NO_x formation increases exponentially with the combustion temperature as observed with the Zeldovich mechanism. The mean of the NO_x emissions per SORT 1 run increases approximately by 25% for B30 RME and B30 UCOME compared to B7.

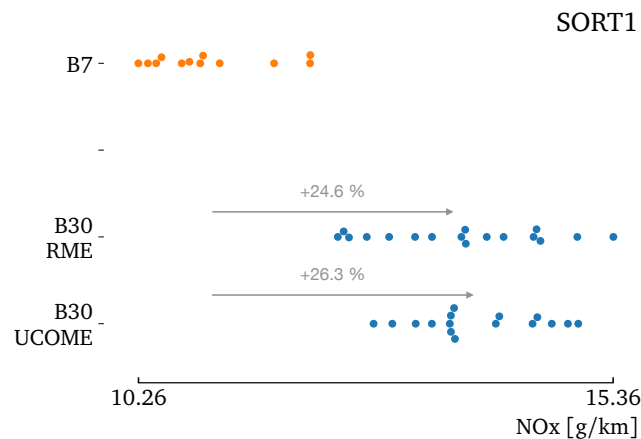


Figure 6. The NO_x emission rate per kilometre of each SORT 1 repetition shows higher NO_x emissions when the bus is fueled with B30 RME and B30 UCOME compared to B7. The maximum measurement uncertainty with 95% probability amounts to 0.14 g/km.

Figure 7 shows the cumulative NO_x emissions of each SORT 1 repetition with the three different fuels. This representation indicates that the different SORT test runs are consistent confirming the quality assurance of the SORT repetitions discussed in Section 2.2.4. All SORT 1 repetitions indicate steep increasing NO_x emissions during accelerations (@0 s, 42 s, 93 s) and close to constant NO_x cumulative emissions during idling (@22–42 s, 73–93 s, 120–140 s). In addition, Figure 7 shows a progressive increase in cumulative NO_x emissions for B30 RME and B30 UCOME compared to B7. The increase in NO_x emissions for B30 fuels is thus not caused by one particular event such as an aggressive acceleration of the SORT cycle. There is an increase of 1.33 g (± 0.8 g) of the mean cumulative NO_x emissions at the end of SORT 1 when switching from B7 to B30 RME.

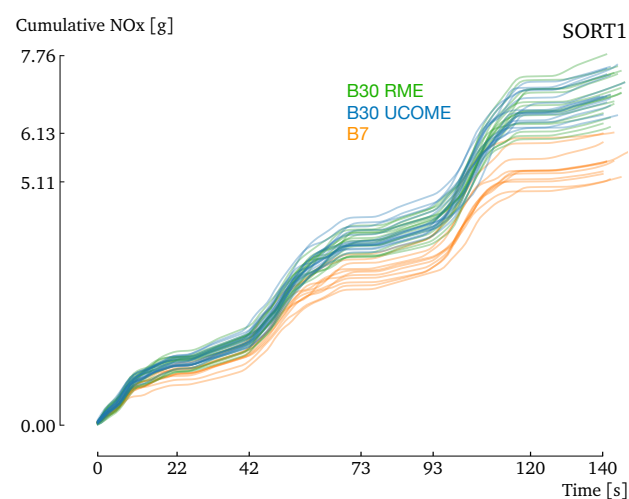


Figure 7. The cumulative NO_x emissions along the SORT 1 test runs indicate an increase in NO_x emissions for B30 RME and B30 UCOME compared to B7.

The NO_x emissions measured during the easy urban SORT 2 cycle follow the same trend as the SORT 1 test runs with higher NO_x emissions for B30 RME and UCOME than for B7 (Figure 8).

However, the increase in NO_x emissions of the B30 RME and UCOME is less important with average increases of 10 to 14% compared to B7. In addition, the NO_x emission rate per kilometre measured during SORT 2 test runs is characterised by a large variance and is lower than during the SORT 1 tests. This is due to the lower accelerations and higher average speed of the SORT 2 cycle. The more aggressive driving dynamics of SORT 1 result in a higher fuel consumption and a higher NO_x emission rate per kilometre.

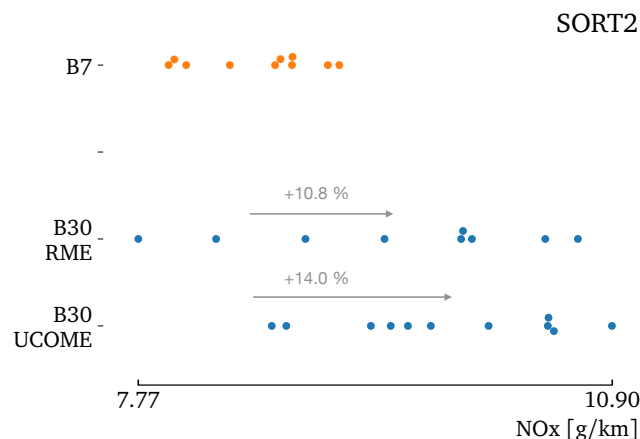


Figure 8. The easy urban SORT 2 (less aggressive dynamics) test runs indicate higher NO_x emissions for B30 RME and B30 UCOME compared to B7 with an average increase varying between 10% and 14%.

Figure 9 highlights the same conclusions for the cumulative NO_x emissions of the SORT 2 repetitions as those discussed for SORT 1. The cumulative NO_x emissions at the end of the SORT 2 cycle are higher than those of the SORT 1 cycle due to the longer distance covered by the SORT 2 cycle. However, relatively, the increase in cumulative NO_x emissions is lower for SORT 2 than for SORT 1.

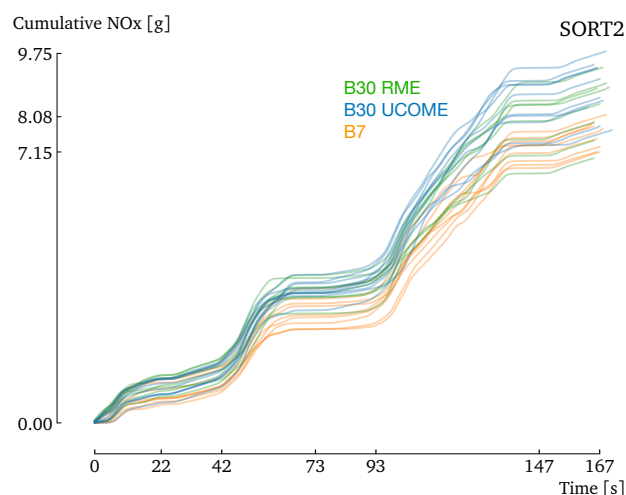


Figure 9. The cumulative NO_x emissions along the SORT 2 test runs indicate, alike for SORT 1, an increase in NO_x emissions for B30 RME and B30 UCOME compared to B7.

Higher tailpipe NO_x emissions of fuels with higher biodiesel concentrations are attributed to both increased NO_x engine out emissions and a lower NO_x reduction efficiency [32]. The NO_x reduction performance depends on the NO₂/NO_x ratio at the SCR inlet with an optimal value of 0.5 [32]. When fueled with B100 the NO₂/NO_x ratio decreases to 0.1–0.2 due to NO₂ deficiency. When the NO₂/NO_x ratio drops below 0.4, the NO_x reduction efficiency drops sharply. Slightly lower

exhaust-gas temperatures are measured for B100 compared to B0 resulting in lower oxidative power of the Diesel Oxidation Catalyst (DOC). Consequently, less NO will be transformed to NO₂ which reduces the NO₂/NO_x ratio at the inlet of the SCR for B100 compared to B0. Mitigation strategies for NO_x increases include among others to add cetane improver additive to the biodiesel blend, change injection timing or add a lean NO_x catalyst [33].

Concerning particle number emissions, a decrease is measured during the heavy urban SORT 1 cycle when the bus is fueled with B30 RME and B30 UCOME compared to B7. In Figure 10, each point represents the PN emission rate per kilometre measured during one SORT 1 cycle repetition. The decrease in particle number emissions is due to the higher oxygen content of biodiesel compared to petrodiesel. In addition, the better combustion and higher heat release rate of the combustion of B30 RME and B30 UCOME is also responsible for the reduction in particulate matter emissions. The mean of the PN emissions per SORT 1 run decreases approximately by 44% for B30 RME and B30 UCOME compared to B7.

The cumulative PN emissions of each SORT 1 repetition confirm the consistency of the repetitions and indicate a progressive and pronounced decrease in PN emissions when fueled with B30 RME and B30 UCOME compared to B7 (Figure 11). Considerably steep increases in PN emissions are measured during accelerations (@0 s, 42 s, 93 s) for all SORT 1 repetitions. During constant speed, deceleration and idling, the cumulative PN emissions remain relatively constant. There is an increase of 7.7×10^{11} particles ($\pm 2.6 \times 10^{11}$ particles) of the mean cumulative PN emissions at the end of SORT 1 when switching from B7 to B30 RME.

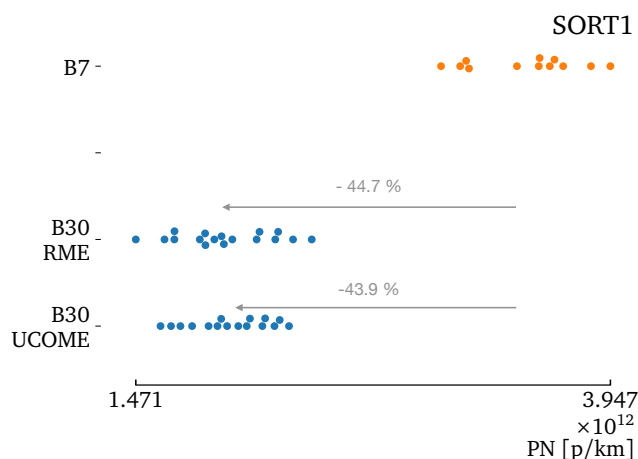


Figure 10. The PN emission rate per kilometre of each SORT 1 repetition shows lower PN emissions when the bus is fueled with B30 RME and B30 UCOME compared to B7.

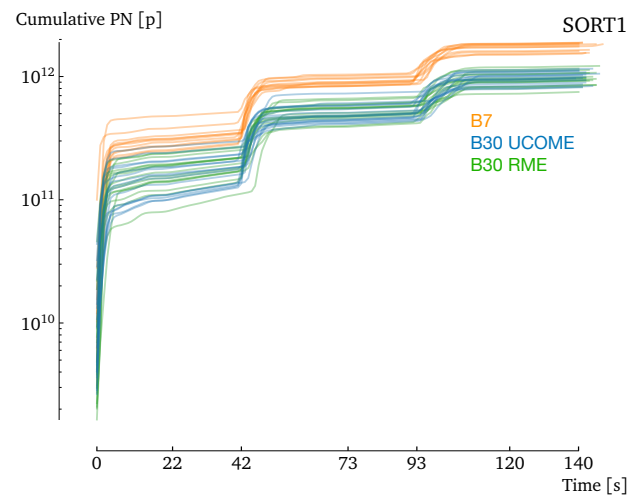


Figure 11. The cumulative PN emissions along the SORT 1 test runs indicate a progressive decrease in PN emissions for B30 RME and B30 UCOME compared to B7.

Concerning the PN emissions measured during the easy urban SORT 2 repetitions, the difference between the B30 RME and B30 UCOME fuels is analogous to those discussed for SORT 1 (Figures 12 and 13). In Figure 12, the average decrease in PN emission rate per kilometre for B30 RME and B30 UCOME varies between 24 and 36% during SORT 2 repetitions. Alike for NO_x emissions, a less pronounced difference in PN emissions between fuels is observed during SORT 2 repetitions compared to SORT 1 repetitions. A possible explanation for the difference in PN emissions between B30 RME and B30 UCOME during SORT 2 is the more efficient combustion occurring during SORT 2 because higher speeds are reached combined with the better quality of UCOME compared to RME. A pretreatment is indeed performed on used cooking oil before transesterification to eliminate their content of impurities such as Free Fatty Acid (FFA), water and solids resulting from their first use. To eliminate water content, used cooking oil is heated to above 100 °C or vacuum distillation is performed at a 0.05 bar pressure [34]. Suspended solids, phospholipids and other impurities are to be washed away with hot water or removed by centrifugation and paper filtration [34].

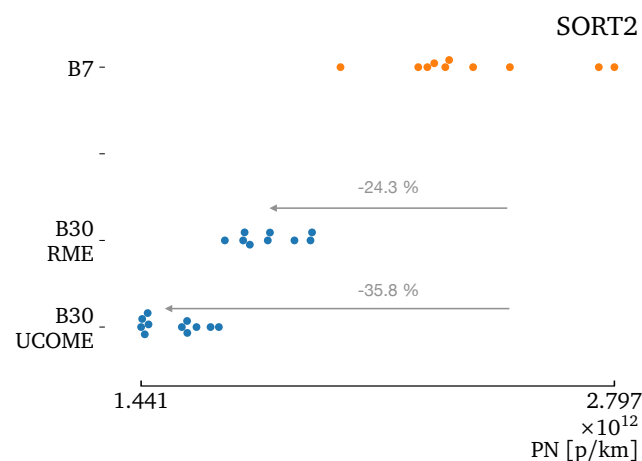


Figure 12. The easy urban SORT 2 test runs indicate lower PN emissions for B30 RME and B30 UCOME compared to B7 with an average decrease varying between 24% and 36%.

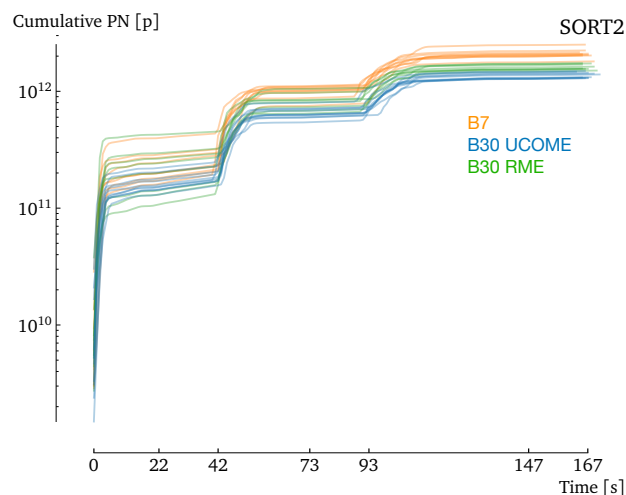


Figure 13. The cumulative PN emissions along the SORT 2 test runs indicate, alike for SORT 1, a decrease in PN emissions for B30 RME and B30 UCOME compared to B7.

Higher DPF regeneration rates and a lower balance point temperature are observed when using biodiesel blends [35]. The balance point is indicative of the performance of a catalysed DPF and is defined as the temperature at which the cDPF is oxidizing soot at the same rate that is being deposited. The difference in DPF performance of soot emissions produced from biodiesel as opposed to diesel engine combustion is due to the higher reactivity in oxygen of biodiesel soot which results on its turn from a more disordered soot structure and higher levels of oxygen [35].

Regarding carbon monoxide emissions, there is no considerable difference measured between B30 RME, B30 UCOME and B7. In Figure 14, the CO emission rate per kilometre of SORT 1 repetitions are spread out on a similar range between 0.86 and 6.62 g/km. The high variance in CO emissions for the three fuels during SORT 1 repetitions is also highlighted by the cumulative CO emissions (Figure 15). CO concentrations on buses are low and close to the lower bound of the CO measurement range. As illustration, the AVL Gas PEMS used in the measurements has an absolute measurement accuracy of 30 ppm for CO which corresponds to the lower CO emission measured on the bus. The average CO emissions for the SORT 1 repetitions of B30 RME and UCOME tend to indicate a reduction compared to B7. Due to the increased oxygen content in the B30 fuels and thus better combustion, less unburned gases are expected.

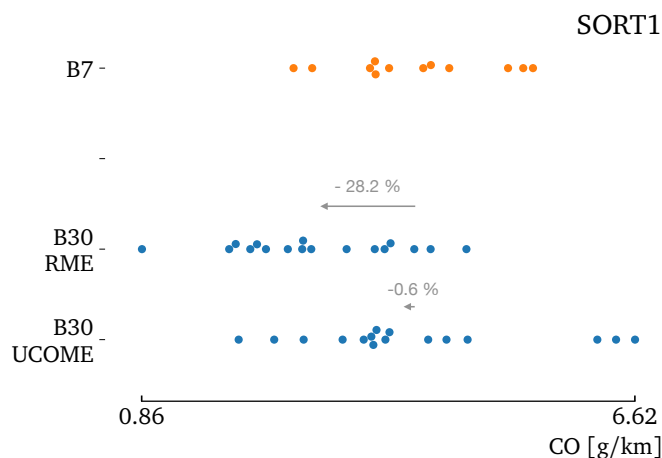


Figure 14. No considerable difference in CO emissions is measured between B30 RME, B30 UCOME and B7 during SORT 1 test runs. The emission rates are low and close to the accuracy of the CO measurement device.

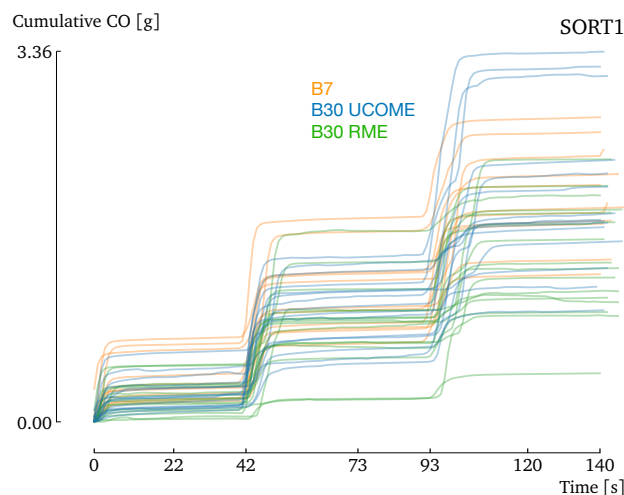


Figure 15. A large spread in cumulative CO emissions is measured among the different SORT repetitions without regard for the used fuel.

Concerning carbon dioxides emitted at the tailpipe, a similar range of emission rate per kilometre is measured on the bus when fueled with B30 RME, B30 UCOME and B7. During SORT 1 repetitions, CO₂ emissions varied between 1193 g/km and 1311 g/km (Figure 16).

A comparison of the relative emission differences between the SORT performed in the framework of this paper and the trends of the HD engine and chassis dynamometer tests reviewed in the introduction indicate more pronounced emissions increases or decreases for the on-road SORT between the biodiesel and conventional diesel fuels. Several factors could influence the change in the emission measurements such as the performed test, the experimental variability and tested engines. A possible cause for the difference in importance of the trends between the SORT tests and the engine and chassis dynamometer is the lack of representativity of real use of engine and chassis dynamometer tests and optimisation of the engine/vehicle for engine/chassis dynamometer tests.

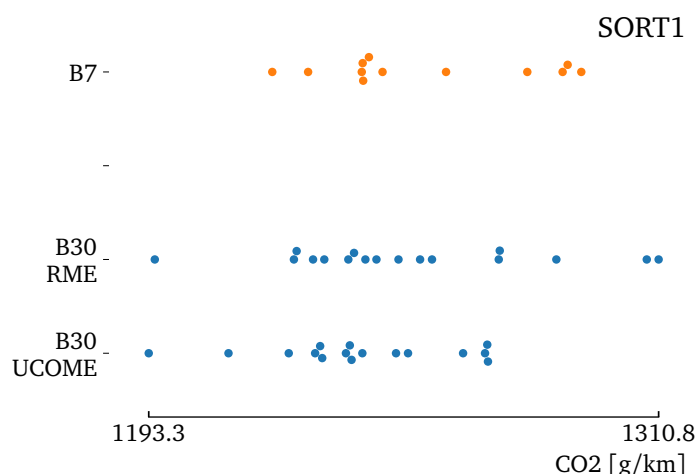


Figure 16. No considerable difference in CO₂ tailpipe emissions is measured during SORT 1 when the bus is fueled with B30 RME, B30 UCOME and B7. The maximum measurement uncertainty with 95% probability amounts to 10.7 g/km.

4. Conclusions

This work compares the tailpipe emissions measured on a public transportation bus and heavy-duty engine fueled with increased concentrations of RME and UCOME. Captive fleets such as public transport buses could benefit from a lower carbon footprint by using fuels with higher biodiesel

content such as B30 (containing 30% in volume of biodiesel). This change not only requires sustainable biodiesel; it also requires to know the impact of B30 fuels on local tailpipe emissions in operation. Hence, this study assesses precisely, based on representative on-road emissions tests and taking into account the measurement uncertainty, what the impact is of fuels with higher concentrations of biodiesel on local tailpipe emissions of buses.

During the on-road heavy urban bus driving, an increase of 24–26% NO_x emissions is measured for B30 RME and B30 UCOME compared to B7. A smaller increase in NO_x emissions with larger variance is measured during the easy urban bus driving that is characterised by a higher average speed. particle number emissions are decreased by 43–45% during the heavy urban bus driving when fueled with B30 RME and B30 UCOME compared to B7. The CO emissions measured during the on-road emissions test are very low and not significant when considering the measurement uncertainty. Equivalent CO₂ emissions are measured on the road for B30 RME, B30 UCOME and B7 as they are characterised by a large variance in the cycle measurements. These on-road emissions measurements are compared with engine dynamometer emissions measurements on heavy-duty engines from the literature indicating less important trends during engine dynamometer emission measurements from the literature compared to SORT. Finally, the effect of aftertreatment systems on emissions from biodiesel are investigated and explained.

Future work should study the calibration of the SCR aftertreatment for higher NO_x emissions as reported for the B30 fuels in this paper during representative on-road tests. This would assure that the benefit in carbon footprint of fuels with higher concentrations of biodiesel would not be accompanied by an increase in NO_x tailpipe pollutants.

Author Contributions: Conceptualization, S.C.; methodology, S.C. and F.B.; formal analysis, S.C.; resources, B.B., F.I., C.M., R.M., and K.M.; writing—original draft preparation, S.C.; writing—review and editing, S.C., F.B., C.M., B.B., H.J., and F.C.; visualization, S.C.; supervision, F.C.; funding acquisition, F.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Bioro Biodiesel Refinery, Cargill.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

2BS	Biomass Biofuel Sustainability voluntary scheme
CI	Compression Ignition
DC	Diffusion Charging
DPF	Diesel Particulate Filter
ECU	Engine Control Unit
EFM	Exhaust Flow Meter
FAME	Fatty Acid Methyl Ester
FID	Flame Ionization Detector
FSN	Filter Smoke Number
GHG	Greenhouse Gas
GPS	Global Positioning System
HC	Hydrocarbon
ISCC	International Sustainability and Carbon Certification
NDIR	Nondispersive Infrared
NDUV	Nondispersive Ultraviolet
OBD	On-Board Diagnostics
PEMS	Portable Emission Measurement System
PN	Particle number
RDE	Real Driving Emissions

RME	Rapeseed Methyl Ester
SCR	Selective Catalytic Reduction
SORT	Standardised On-Road Test cycle
UCOME	Used Cooking Oil Methyl Ester
UITP	International Association of Public Transport
VPR	Volatile Particle Remover
WTT	Well-to-Tank
WWHD	Worldwide Harmonized Heavy Duty

Appendix A. Dry-to-Wet Correction Factor

The dry-to-wet correction factor $CF_{dry/wet}$ of the ISO16183 standard

$$CF_{dry/wet} = \frac{1}{1 + \alpha * 0.005 * (X_{CO_2,dry} + X_{CO,dry}) - \frac{1.608 * H_a}{1000 + (1.608 * H_a)}}$$

where α is the molar hydrogen ratio of the fuel (-), H_a is the absolute humidity expressed in gram of water per kilogram of dry air (g/kg), $X_{CO_2,dry}$ is the dry fraction of CO_2 measured by the PEMS (%) and $X_{CO,dry}$ is the fraction of CO measured by the PEMS (%).

Appendix B. NOx Correction Factor for Ambient Conditions

The NOx correction factor for ambient conditions CF_{NOx} of the ISO16183 standard for compression ignition engines

$$CF_{NOx} = \frac{1}{1 - 0.0182 * (H_a - 10.71) + 0.0045 * (T_{amb} - 298)}$$

where H_a is the absolute humidity expressed in gram of water per kilogram of dry air (g/kg), T_{amb} is the ambient temperature (K).

References

1. European Parliament and Council of European Union. Directive (EU) 2018/2001 on the Promotion of the Use of Energy from Renewable Sources. 2018. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018L2001&from=EN#d1e40-82-1> (accessed on 26 September 2020).
2. Abomohra, A.E.F.; Elsayed, M.; Esakkimuthu, S.; El-Sheekh, M.; Hanelt, D. Potential of fat, oil and grease (FOG) for biodiesel production: A critical review on the recent progress and future perspectives. *Prog. Energy Combust. Sci.* **2020**, *81*, 100868, doi:10.1016/j.pecs.2020.100868.
3. Agarwal, A.K.; Gupta, J.G.; Dhar, A. Potential and challenges for large-scale application of biodiesel in automotive sector. *Prog. Energy Combust. Sci.* **2017**, *61*, 113–149, doi:10.1016/j.pecs.2017.03.002.
4. Farobie, O.; Matsumura, Y. State of the art of biodiesel production under supercritical conditions. *Prog. Energy Combust. Sci.* **2017**, *63*, 173–203, doi:10.1016/j.pecs.2017.08.001.
5. Knothe, G.; Razon, L.F. Biodiesel fuels. *Prog. Energy Combust. Sci.* **2017**, *58*, 36–59, doi:10.1016/j.pecs.2016.08.001.
6. Du Transport SRWT, S.R.W. Rapport D'activité 2018. Available online: <http://rapportannuel.letec.be/otw/#le-tec-en-chiffres> (accessed on 15 July 2019).
7. Lijn, D. Jaarverslag 2018. Available online: https://static.delijn.be/Images/jaarverslag%202018_totaal_tcm3-22501.pdf (accessed on 15 July 2019).
8. Des Transports Inter-Communaux Bruxellois STIB-MIVB, S. Statistiques 2018. Available online: http://www.stib-mivb.be/irj/go/km/docs/WEBSITE_RES/Attachments/Corporate/Statistiques/2018/STIB_RA2018_Statistiques_EN_HD.pdf (accessed on 15 July 2019).

9. Lapuerta, M.; Armas, O.; Rodríguez-Fernández, J. Effect of biodiesel fuels on diesel engine emissions. *Prog. Energy Combust. Sci.* **2008**, *34*, 198–223, doi:10.1016/j.pecs.2007.07.001.
10. Heidari, S.; Najjar, R.; Burnens, G.; Awad, S.; Tazerout, M. Experimental Investigation of Emission, Combustion, and Energy Performance of a Novel Diesel/Colza Oil Fuel Microemulsion in a Direct-Injection Diesel Engine. *Energy Fuels* **2018**, *32*, 10923–10932, doi:10.1021/acs.energyfuels.7b03181.
11. Ashikhmin, A.; Piskunov, M.; Yanovsky, V.; Yan, W.M. Properties and Phase Behavior of Water-in-Diesel Microemulsion Fuels Stabilized by Nonionic Surfactants in Combination with Aliphatic Alcohol. *Energy Fuels* **2020**, *34*, 2135–2142, doi:10.1021/acs.energyfuels.9b03493.
12. Ashikhmin, A.; Piskunov, M.; Roisman, I.; Yanovsky, V. Thermal stability control of the water-in-diesel microemulsion fuel produced by using a nonionic surfactant combined with aliphatic alcohols. *J. Dispers. Sci. Technol.* **2020**, *41*, 771–778, doi:10.1080/01932691.2019.1634583.
13. Attaphong, C.; Sabatini, D.A. Phase Behaviors of Vegetable Oil-Based Microemulsion Fuels: The Effects of Temperatures, Surfactants, Oils, and Water in Ethanol. *Energy Fuels* **2013**, *27*, 6773–6780, doi:10.1021/ef401441a.
14. Chandra, R.; Kumar, R. Fuel Properties of Some Stable Alcohol–Diesel Microemulsions for Their Use in Compression Ignition Engines. *Energy Fuels* **2007**, *21*, 3410–3414, doi:10.1021/ef0701788.
15. Giakoumis, E.G.; Rakopoulos, C.D.; Dimaratos, A.M.; Rakopoulos, D.C. Exhaust emissions of diesel engines operating under transient conditions with biodiesel fuel blends. *Prog. Energy Combust. Sci.* **2012**, *38*, 691–715, doi:10.1016/j.pecs.2012.05.002.
16. Sun, J.; Caton, J.A.; Jacobs, T.J. Oxides of nitrogen emissions from biodiesel-fueled diesel engines. *Prog. Energy Combust. Sci.* **2010**, *36*, 677–695, doi:10.1016/j.pecs.2010.02.004.
17. Rajaeifara, M.A.; Tabatabaei, M.; Aghbashlo, M.; Nizamif, A.S.; Heidrich, O. Emissions from urban bus fleets running on biodiesel blends under real-world operating conditions: Implications for designing future case studies. *Renew. Sustain. Energy Rev.* **2019**, *111*, 276–292.
18. United States Environmental Protection Agency *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions*; Draft Technical Report, EPA420-P-02-001. National Service Center for Environmental Publications (NSCEP), Cincinnati, OH, United States; 2002.
19. Anderson, L. Effects of Biodiesel Fuels Use on Vehicle Emissions. *J. Sustain. Energy Environ.* **2012**, *3*, 35–47.
20. Hoekman, S.K.; Gertler, A.; Broch, A.; Robbins, C. *Investigation of Biodistillates as Potential Blendstocks for Transportation Fuels*; Crc project no. avfl-17; Coordinating Research Council, Inc. Alpharetta, GA, United States; 2009.
21. Merksiz, J.; Fuc, P.; Lijewski, P.; Kozak, M. *Rapeseed Oil Methyl Esters (RME) as Fuel for Urban Transport*; Technical report; 2016. Available online: <https://www.intechopen.com/books/alternative-fuels-technical-and-environmental-conditions/rapeseed-oil-methyl-esters-rme-as-fuel-for-urban-transport> (accessed on 31 August 2020).
22. SA, C.B. Bioro Biodiesel Refinery Plant—Certified Sustainable Biodiesel Supply. Available online: <https://www.cargill.com/agriculture/bioro-biodiesel-refinery> (accessed on 19 November 2019).
23. Martin, C.; Wagenknecht, T. *UITP Project ‘SORT’ Standardised On-Road Test Cycles*; UITP, Brussels, Belgium, 2014.
24. Giechaskiel, B.; Riccobono, F.; Mendoza-Villafuerte, P.; Grigoratos, T. *Particle Number (PN)—Portable Emissions Measurement Systems (PEMS)*; Technical report; Publications Office of the European Union, Luxembourg, Luxembourg; 2016, doi:10.2788/052796.
25. European Parliament and Council of European Union. Regulation No 49 of the Economic Commission for Europe of the United Nations (UN/ECE). 2013. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A42013X0624%2801%29> (accessed on 26 September 2020).
26. GmbH, A.V.L. *User’s Guide AVL CONCERTO M.O.V.E. V4.3 up to v4.8*; Technical report: AVL, Graz, Austria; 2016.
27. Pochet, M.; Jeanmart, H.; Contino, F. Uncertainty Propagation of Internal Combustion Engine Experiments: From Raw Measurements to Post-Processed Uncertainties. *Int. J. Engine Res.* **2019**, *21*, 1709–1737.
28. GmbH, A.V.L. *AVL M.O.V.E. Gas PEMS iS Product Guide*; Technical report, AT6103E Rev. 05: AVL, Graz, Austria; 2017.
29. GmbH, A.V.L. *AVL M.O.V.E. EFM—Exhaust Flow Meter Product Guide*; Technical report, AT6674E Rev. 00: AVL, Graz, Austria; 2015.

30. Gmbh, N.P.S. *Partector 2 Aerosol Dosimeter Operation Manual*; Technical report; Naneos Particle solutions, Windisch, Switzerland ; 2018.
31. Labs, S. I2C Humidity and Temperature Sensor. Available online: <https://www.silabs.com/documents/public/data-sheets/Si7021-A20.pdf> (accessed on 20 December 2019).
32. Mizushima, N.; Murata, Y.; Suzuki, H.; Ishii, H.; Goto, Y.; Kawano, D. Effect of Biodiesel on NO_x Reduction Performance of Urea-SCR System. *Sae Int. J. Fuels Lubr.* **2010**, *3*, 1012–1020.
33. McCormick, R.; Alvarez, J.; Graboski, M. *NO_x Solutions for Biodiesel*; Technical report; National Renewable Energy Laboratory: Golden, CO , United States; 2003.
34. RecOil. *Assessment of Best Practices in UCO Processing and Biodiesel Distribution. D4.3—Guide on UCO Processing and Biodiesel Distribution Methods*; Technical University of Crete: Chania, Greece; 2013.
35. Williams, A.; McCormick, R.L.; Hayes, R.R.; Ireland, J.; Fang, H.L. Effect of Biodiesel Blends on Diesel Particulate Filter Performance. *SAE Trans.* **2006**, *115*, 563–573.



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).