energies

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Exhaust Emissions from a Hybrid City Bus Fuelled by Conventional and Oxygenated Fuel

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Abstract: City buses are one of the main means of public transport in cities. As they move in a limited and densely populated area and are intensively exploited, it is particularly important that they are environmentally friendly. There are many ways to reduce emissions from city buses, including the use of hybrid propulsion. Another way is to use low-emission fuels. This article presents the results of the emission tests of an 18 m articulated city bus with a serial hybrid drive fuelled comparatively by conventional diesel fuel and oxygenated fuel containing 10% *v*/*v* of triethylene glycol dimethyl ether (TEGDME). The emission tests were carried out during the actual operation of the bus on a route in Poznań (Poland) and over the SORT cycles. The obtained test results were compared also with the results obtained for a conventional bus. The reduction in emissions of some exhaust components was found when the hybrid bus was fuelled with oxygenated fuel during its actual operation on the bus route. There was a reduction in CO emissions by ~50% and NO_x emissions by ~10%. Almost identical levels of PM and HC emissions and smoke opacity were observed for both fuels. In the SORT cycles, the differences in the emissions obtained for both types of fuel were small. In general, for the hybrid bus, a lower influence of oxygenated fuel on emissions was recorded than for the conventional bus.

Keywords: exhaust emissions; city bus; hybrid bus; oxygenated diesel fuel

Citation: Kozak, M.; Lijewski, P.; Waligórski, M. Exhaust Emissions from a Hybrid City Bus Fuelled by Conventional and Oxygenated Fuel. *Energies* **2022**, *15*, 1123. https://doi.org/10.3390/en15031123

Academic Editors: Karol F. Abramek and Evangelos Giakoumis

Received: 30 October 2021
Accepted: 25 January 2022
Published: 3 February 2022

1. Introduction

The areas with the worst air quality include large urban agglomerations [1–3]. On the one hand, there is the highest density of moving vehicles, and therefore a huge number of emission sources. On the other hand, vehicle traffic conditions in large cities are usually unfavourable (low average speed, frequent braking, stopping and accelerating) and favour high fuel consumption and high exhaust emissions. In urban agglomerations, city buses, along with trams, metro and sometimes trolleybuses, are usually the main element of public transport. Traffic conditions of city-buses are particularly unfavourable here due to the necessity of frequent stops at bus stops and traffic congestion. Additionally, in cities, the dense development of buildings hinders the dispersion of exhaust gases emitted by buses and other vehicles. At the same time, a large number of people are exposed to the pollution because of the high population density in cities. It is well known that in buses, the most common source of propulsion, also in hybrid solutions, is the diesel engine. The toxic effects of diesel engine exhaust on the human body are well known [4–6], including carcinogenic effects [7,8]. It is therefore understandable that reducing harmful exhaust emissions from city buses is particularly desirable. Over the last 20 years or so, exhaust emissions from diesel vehicles have been significantly reduced. First of all, thanks to the use of advanced injection systems and effective exhaust aftertreatment systems [9–12]. This is perfectly illustrated by the lower and lower levels of exhaust emissions permitted by law [13,14]. The introduction of reformulated diesel fuels, containing less than 10 ppm of sulphur, also played an important role.

From the legal point of view, reducing the exhaust emissions is forced by increasingly rigorous emission limits as well as stricter and more extensive measurement procedures [15].

In this respect, note in particular that emission tests are carried out in real operating conditions [16–21]. These studies provide more reliable results, which sometimes critically verify theoretical assumptions or the predictions made on their basis. For example, in studies by Liu et al. [22] the exhaust emissions of buses were investigated in real conditions. A total of 234 city buses with different drive systems and emission standards were tested, including a large sample of Euro V buses (59 conventional and 26 hybrid). Based on this research, it was found that hybrid buses may emit more PN (particle number), NO_x and HC than buses with conventional drive. Other results presented by Keramydas et al. [23] have shown that on some urban routes, hybrid buses may consume more fuel than conventional diesel buses. In turn, Dreier et al. in their research they found that plug-in hybrid bus provide reductions in greenhouse gas emissions of up to 72% [24].

Due to the ongoing COVID-19 pandemic, forecasts regarding the development of transport and other branches of the economy are subject to considerable uncertainty [25]. Nevertheless, the forecasts presented by the OECD in Transport Outlook 2021, even in the most pessimistic variant, predict an increase in the demand for passenger transport in cities [26]. Total urban passenger transport demand is projected to grow by 59% to 2030 and 163% by 2050 from the base year 2015 under the Recover scenario. Characteristically, all scenarios are expected to increase the share of public transport at the expense of individual (private) transport.

Four main energy carriers are available for city buses: fossil fuels, biofuels, electricity and hydrogen. For all of these options, there are different application solutions, using one fuel or a combination of more than one energy carrier. The prospects for the development of modern city buses were studied under the European initiative CIVITAS (Cleaner and better transport in cities). The results obtained in this project show that buses powered by: compressed natural gas, electricity, second-generation biofuels and hybrid configurations combining electricity with hydrogen or a diesel engine are considered as the most promising in terms of technology and environment [27]. There are many studies available in the literature describing the environmental benefits associated with the use of the above-mentioned technologies, see, e.g., in [28–33].

Diesel engine is at present, and certainly will remain in the near future, the dominant drive in city buses. The service life of a city bus in Polish conditions is ~15 years. Therefore, it is justified to look for solutions reducing the toxicity of exhaust gases emitted from these vehicles. One possible solution is the use of oxygenated fuels. At the turn of the 20th and 21st centuries, many projects were implemented in this area, which confirmed the beneficial effect of oxygenated fuels on the composition of exhaust gases from diesel engines [34–39]. Usually, reductions in the emissions of incomplete combustion products: PM, CO and HC were observed, while maintaining an acceptable NO_x emissions. A reduction in PM emissions is regarded as the main environmental benefit of oxygenated diesel fuel application. However, in the view of minor changes in NO_x emissions, an improvement is also achieved with regard to so-called PM/NO_x trade-off. The advantage of synthetic oxygenated compounds compared to the commonly used fatty acid methyl esters (FAME) is the high oxygen content—e.g., ~36% m/m for glymes, and even 53% for dimethyl carbonate, compared to only ~10% for FAME. Thus, even a small addition of such synthetic oxygenates made it possible to achieve an oxygen concentration in the fuel that would reduce PM emissions, while not significantly affecting the fuel's physical properties.

Similarly, the authors of this study conducted in the past extensive research on the influence of oxygenated fuels on the exhaust emissions from diesel vehicles [40–43]. Among the 12 tested oxygenated compounds, PM emissions were reduced the most by carbonates; however, taking into account the PM/NO_x trade-off, glycol ethers were the most favourable oxygenates. Among the six tested compounds from the glycol ethers group, in the authors' research the most favourable results were obtained for triethylene glycol dimethyl ether. With the content of 10% v/v of TEGDME in diesel fuel, for a Euro 4 diesel passenger car over the NEDC cycle, PM emissions were reduced by 32%, HC by 34%, CO by 30%, with no changes in NO_x emissions [44]. For this reason, the authors decided to use this oxygenated compound in the studies presented in this article.

The studies published by other authors also show favourable changes in exhaust emissions associated with application of glycol ethers as diesel fuel components. For example, mention can be made of the work of Delfort et al. [35]. They tested passenger car emissions over the NEDC and achieved a reduction in PM emissions. The study by Hallgren and Heywood [36] also reveals a reduction of PM emissions with the use of glycol ethers as diesel fuel components. Additionally, in this research it was also established that oxygenated compounds reduce mainly soot fraction, and only slightly soluble organic fraction. In another study (Yeh et al. [39]), it was found that when glycol ethers are used, except of PM, also CO and HC emissions are reduced, however, NO_x emissions increase. Some further examples of studies showing the favourable effects of glycol ethers in diesel fuels on exhaust emissions can be given, including such as Porai et al. [45], Dumitrescu et al. [46], Serhan et al. [47] and Pellegrini et al. [48].

Despite the development of exhaust gas aftertreatment systems, oxygenated fuels are still of interest to researchers, as evidenced by the emerging scientific works in this field, see, e.g., in [49–52]. The authors of this study also decided to investigate the effect of diesel fuel containing triethylene glycol dimethyl ether on road exhaust emissions of a hybrid bus. Unfavourable operating conditions of city bus engines may favour the benefits of using oxygenated diesel fuels. To the best of the authors' knowledge, studies such as those undertaken in this article have not yet been published anywhere.

It should be emphasised that the driving conditions of a vehicle have a decisive influence on the operating conditions of its engine. These, in turn, determine the level of fuel consumption and exhaust emissions [53–55]. Therefore, particularly valuable results are provided by measurements on real routes of city buses, possibly in test cycles mapping various road traffic conditions. This approach was used in this work.

2. Materials and Methods

2.1. Test Fuels

During the emissions tests described in this study a fuel mixture consisting of 90% by volume of conventional diesel fuel and 10% by volume of triethylene glycol dimethyl ether (also called triglyme, abbreviation TEGDME) was used. As already mentioned, the authors used this glycol ether in their earlier research on the influence of oxygenated fuels on the exhaust emissions from diesel passenger cars and TEGDME turned out to be one of the most effective oxygenated compounds in reducing exhaust emissions [30]. Detailed results of the research conducted by the authors on the influence of TEGDME on exhaust emissions from a diesel passenger car can be found in [27]. The physicochemical properties of triethylene glycol dimethyl ether are shown in Table 1. Comparative exhaust emissions measurements were performed with conventional diesel fuel (EN 590: 2014), the same that was used to blend the oxygenated fuel. Some properties of this diesel fuel are presented in Table 2.

2.2. Research Apparatus

The SEMTECH DS portable emissions measurement system was used to measure the emissions of gaseous exhaust components in this study. This analyser has its own weather station, GPS module and communication system with the vehicle's on-board diagnostic system. The sequence of exhaust gas flow through the individual components of the SEMTECH DS analyser is shown in Figure 1. The methods and accuracies of the measurement of individual exhaust gas components are shown in Table 3.

Table 1. Some properties of triethylene glycol dimethyl ether (triglyme, TEGDME).

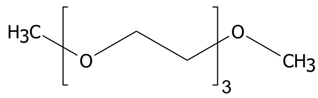
Property	Unit	Value
Molecular weight	amu	178.23
Oxygen content	% (*m*/*m*)	36.0
Boiling point	°C	220
Melting point	°C	−45
Density @ 20 °C	kg/m^3	987
Viscosity @ 20 °C	mm^2/s	2.5
Flash point	°C	113
Cetane number (calculated)	–	144
Chemical formula		 $C_8H_{18}O_4$

Table 2. Some properties of conventional diesel fuel used in the tests.

Properties		Unit	Value
Cetane number		–	52.8
Cetane index		–	53.4
Density @ 20 °C		kg/m^3	827.7
Sulphur content		ppm	8.8
Viscosity	@ 20 °C	mm^2/s	4.096
	@ 40 °C	mm^2/s	2.607
Distillation	E250	% (*v*/*v*)	38.1
	E350	% (*v*/*v*)	–
	T95	°C	332.3
	FBP	°C	343.7
Aromatic Hydrocarbons	Total aromatics	% (*m*/*m*)	20.7
	Monoaromatics	% (*m*/*m*)	18.8
	Diaromatics	% (*m*/*m*)	1.7
	Tri + aromatics	% (*m*/*m*)	0.2
	Total PAH	% (*m*/*m*)	1.9

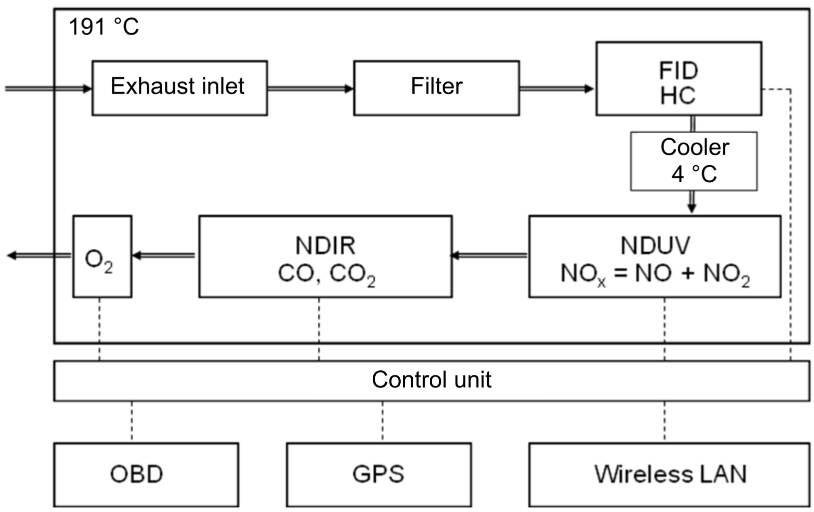


Figure 1. Exhaust gas flow through the SEMTECH DS analyser.

Table 3. Characteristics of the SEMTECH DS exhaust gas analyser.

Exhaust Component	Measuring Method	Accuracy
CO	NDIR, range: 0–10%	±3%
HC	FID, range: 0–10,000 ppm	±2.5%
NO_x	NDUV, range: 0–3000 ppm	±3%
CO_2	NDIR, range: 0–20%	±3%

The on-board AVL 483 Micro Soot Sensor analyser was used to measure particulate matter emissions. This analyser works on a photoacoustic principle. Its operational parameters are presented in Table 4. Micro Soot Sensor enables continuous measurement of the concentration of particles in diluted exhaust gas. Exhaust gas mass flow was measured with a 4″ diameter flowmeter.

Table 4. Specifications of the AVL 483 MSS particulate analyser.

Parameter	Value
Measuring range	0–50 mg/m^3
Resolution	0.001 mg/m^3
Dilution factor	5000
Sampling of exhaust gas	2 dm^3/min
Analyzer operating conditions	temperature: 5–45 °C humidity: 0–95%

2.3. Research Driving Cycles

The hybrid bus was tested on the actual public transport route number 76 in the city of Poznań. This route had 46 stops and started in the northern part of the city. Then it ran through the very centre and ended in the southern part of the city, near the A2 highway. The parameters of this route are presented in Table 5, and its course on the city map in Figure 2. During the tests, the bus travelled the route twice using each fuel. The tests were carried out on the following days, in the same afternoon rush hours, to ensure the most similar test conditions for both types of fuel.

The emission tests of city bused fuelled with oxygenated diesel fuel were conducted also over SORT cycles (Standardised On-Road Tests). SORT driving cycles were developed by the International Association of Public Transport UITP and are designed in three varieties representing conditions as follows:

- crowded city traffic (SORT 1—*heavy urban*),
- moderate urban traffic (SORT 2—*easy urban*),
- suburban traffic (SORT 3—*suburban*).

The courses of the SORT driving tests are shown in Figure 3 and their characteristics in Table 6. The bus tests over SORT cycles were carried out on a runway.

Table 5. Characteristics of the bus route no. 76 in the city of Poznań on which the emissions of hybrid bus were tested.

Parameter	Unit	Value
Total distance	km	16
Average speed	km/h	18–22
Top speed	km/h	60
Stop share	%	20–30
Number of stops	–	46
Route type (characteristics)	–	The very centre of the city and the main communication arteries

Figure 2. The course of the bus route number 76 in the city of Poznań on which the emissions of hybrid bus were tested.

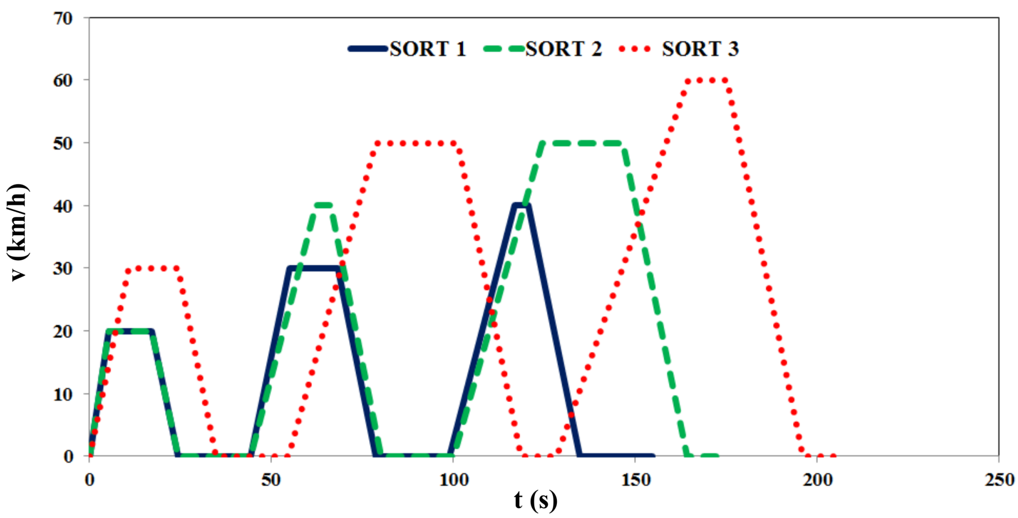


Figure 3. SORT 1, 2 and 3 driving cycles.

Table 6. Characteristics of SORT driving cycles.

	SORT 1	SORT 2	SORT 3
Average speed (km/h)	12.6	18.6	26.3
Stop share (%)	39.7	33.4	20.1
Number of stops per km (1/km)	5.8	3.3	2.1
Profile (trapezium) 1: constant speed (km/h)/distance (m)	20/100	20/100	30/200
Profile (trapezium) 1: acceleration (m/s^2)	1.03	1.03	0.77
Profile (trapezium) 2: constant speed (km/h)/distance (m)	20/200	40/220	50/600
Profile (trapezium) 2: acceleration (m/s^2)	0.77	0.62	0.57
Profile (trapezium) 3: constant speed (km/h)/distance (m)	40/220	50/600	60/650
Profile (trapezium) 3: acceleration (m/s^2)	0.62	0.57	0.46
Stop time after each profile (s)	20/20/20	20/20/20	20/10/10
Total distance (m)	520	920	1450
Deceleration (m/s^2)	0.8	0.8	0.8

2.4. Test Vehicles

The test vehicle was the 18 m long articulated city bus Solaris Urbino 18 Hybrid, which was equipped with a serial hybrid drive system. Technical specification of this bus is presented in Table 7. The bus was equipped with a valve in the fuel tank, which allowed for complete emptying of the tank and easy and quick change of the type of fuel (conventional/oxygenated). The view of the bus during the tests is shown in Figure 4, and in Figure 5, the view of the measurement apparatus installed in the bus.

The results of conventional bus emissions, which are used in the further part of the paper for comparison with the results of the hybrid bus, were obtained with the use of the Solaris Urbino 18 m city articulated bus, the technical data of which are presented in Table 8.

Table 7. Specifications of the hybrid city bus used in the tests.

Parameter	Value
Length	18 m
Drivetrain type	Serial hybrid
Electric motor maximum power	240 kW
Electric generator maximum power	200 kW
Combustion engine type	Diesel, six-cylinder, in-line
Displacement	6.7 dm^3
Compression ratio	17.3
Maximum power	209 kW @ 2300 rpm
Maximum torque	1008 Nm @ 1200 rpm
Combustion system	Direct injection, common rail injection system, turbocharging with intercooling
Exhaust gas recirculation	Electronically controlled, cooled
Exhaust aftertreatment	DOC/DPF/SCR
Emission standard	Euro VI

Figure 4. The Solaris Urbino 18 Hybrid bus with the exhaust gas sampling system.

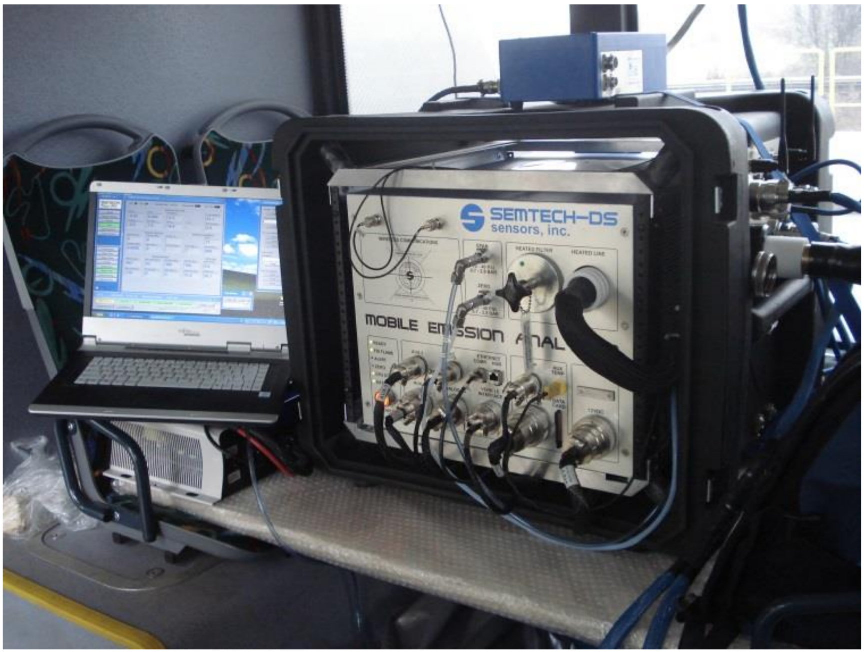


Figure 5. A view of the measuring apparatus during the tests.

Table 8. Specifications of the conventional city bus used in the tests.

Parameter	Value
Length	18 m
Engine type	Diesel, six-cylinder, in-line
Displacement	9.2 dm^3
Compression ratio	17.4
Maximum power	231 kW @ 1900 rpm
Maximum torque	1275 Nm @ 1100–1710 rpm
Combustion system	Direct injection, common rail injection system, turbocharging with intercooling
Exhaust gas recirculation	Electronically controlled, cooled
Exhaust aftertreatment	DOC/DPF/SCR
Emission standard	EEV

3. Test Results and Discussion

3.1. Hybrid Bus Test Results

Figure 6 shows the results of the average road emissions on the route no. 76 in Poznań of the hybrid bus fuelled comparatively by conventional diesel fuel and oxygenated fuel. As it can be seen, favourable changes in emissions of CO and NO_x took place when the bus was fuelled with oxygenated fuel. For HC, PM and smoke opacity (N), similar results were obtained. The literature, see, e.g., in [56,57], describes the reduction of CO emissions with the use of high-cetane oxygenated fuels and it seems that this is the case here. Similarly, slightly lower NO_x emissions for oxygenated fuel may be due to its better ignition quality, which translates into smoother combustion and less intense nitrogen oxides formation. However, the only slight differences in emissions for both fuels are probably the result of the effective operation of the exhaust gas aftertreatment systems.

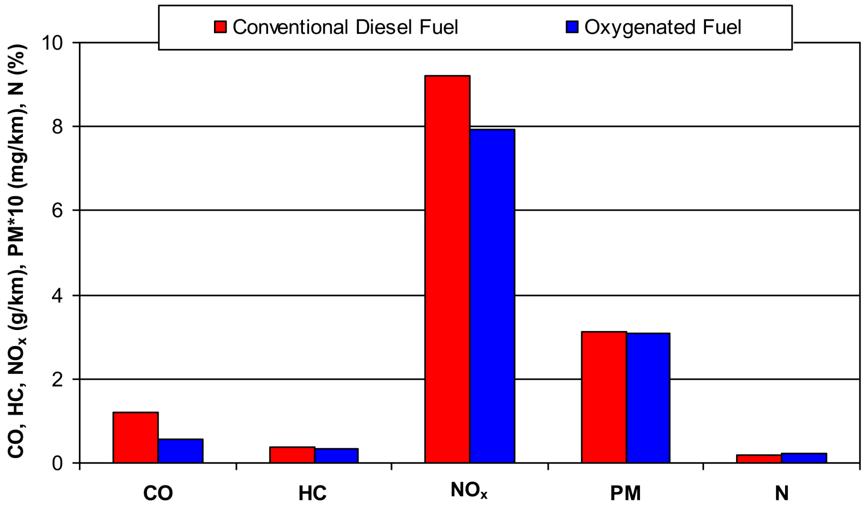


Figure 6. Average road emissions from the Solaris Urbino 18 Hybrid bus fuelled by conventional diesel fuel and oxygenated fuel on the route no. 76 of the Municipal Transport Company in Poznań.

In the SORT cycles (Figures 7–9), no significant influence of oxygenated fuel on the emissions of individual exhaust gas components was found. Characteristic, however, is lower emission, in particular NO_x, for cycles with a milder course, i.e., the highest emission was recorded for SORT 1 and the lowest for SORT 3.

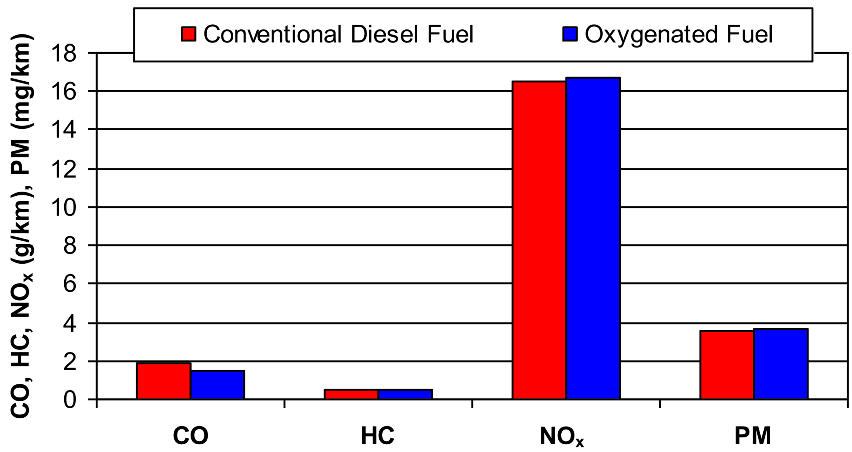


Figure 7. Average road emissions in the SORT 1 cycle from the Solaris Urbino 18 Hybrid bus fuelled by conventional diesel fuel and oxygenated fuel.

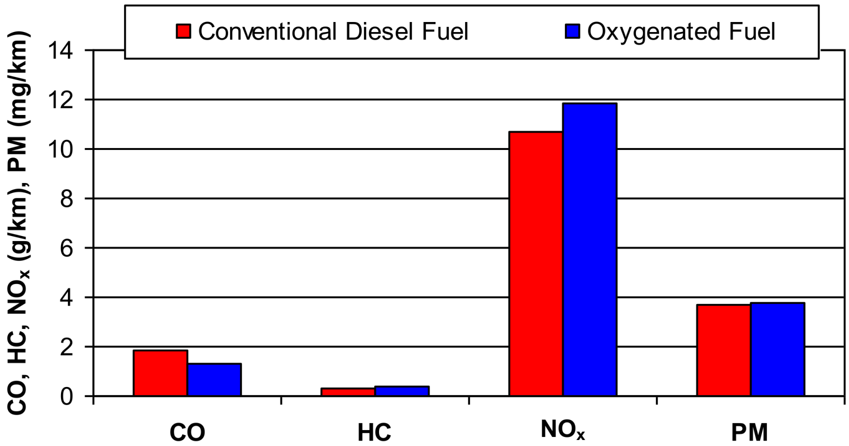


Figure 8. Average road emissions in the SORT 2 cycle from the Solaris Urbino 18 Hybrid bus fuelled by conventional diesel fuel and oxygenated fuel.

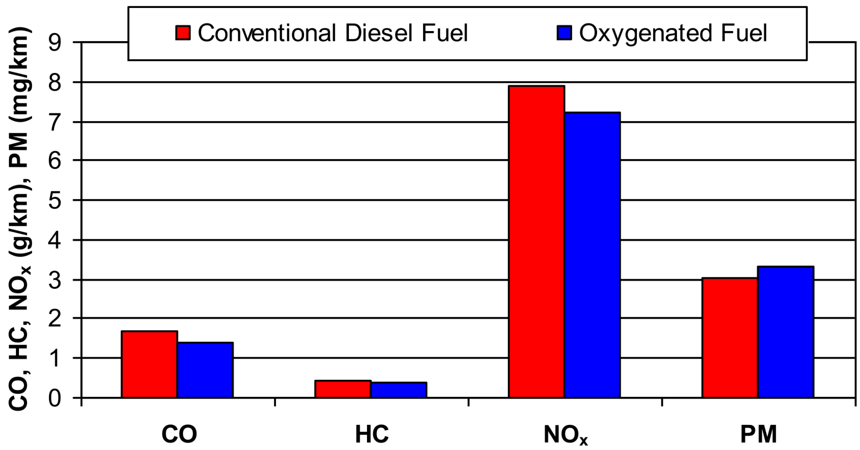


Figure 9. Average road emissions in the SORT 3 cycle from the Solaris Urbino 18 Hybrid bus fuelled by conventional diesel fuel and oxygenated fuel.

3.2. Comparison of Exhaust Emissions for Hybrid and Conventional City Buses

Figures 10–13 show a comparison of CO, HC, NO_x and PM road emissions of hybrid and conventional bus fuelled by conventional diesel fuel and oxygenated fuel, over the various SORT cycles.

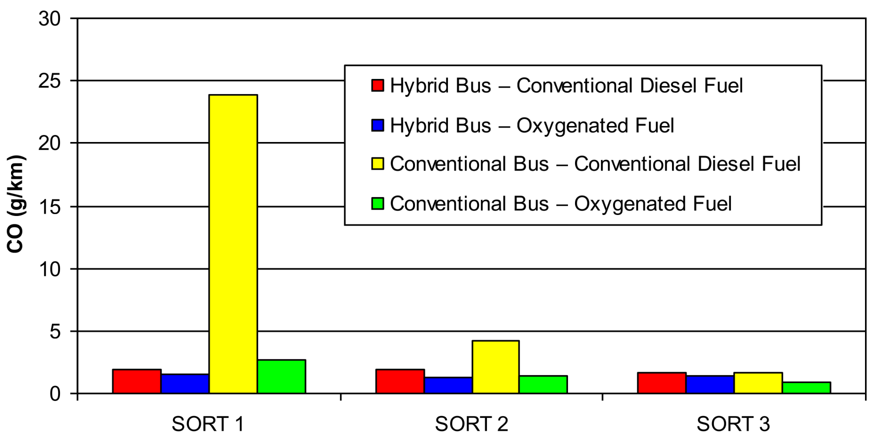


Figure 10. Comparison of CO emissions of serial hybrid and conventional city buses running on conventional and oxygenated diesel fuel, over the SORT cycles.

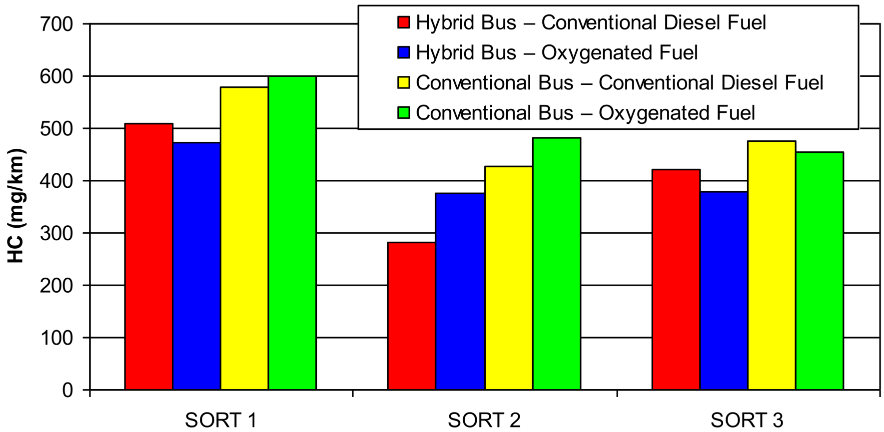


Figure 11. Comparison of HC emissions of serial hybrid and conventional city buses running on conventional and oxygenated diesel fuel, over the SORT cycles.

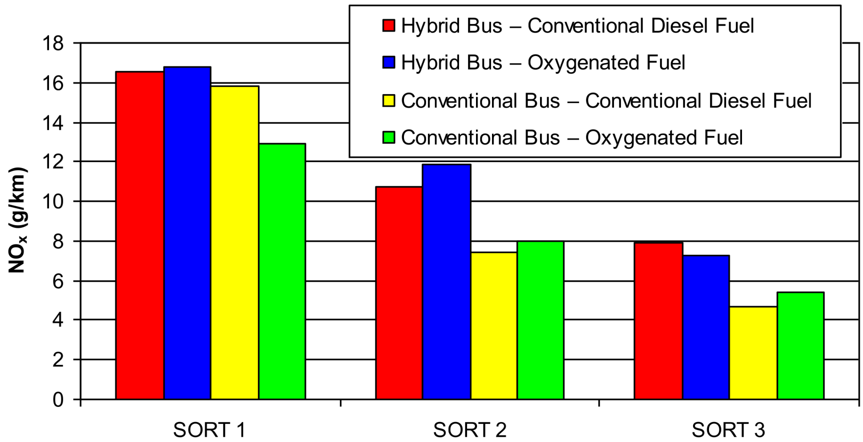


Figure 12. Comparison of NO_x emissions of serial hybrid and conventional city buses running on conventional and oxygenated diesel fuel, over the SORT cycles.

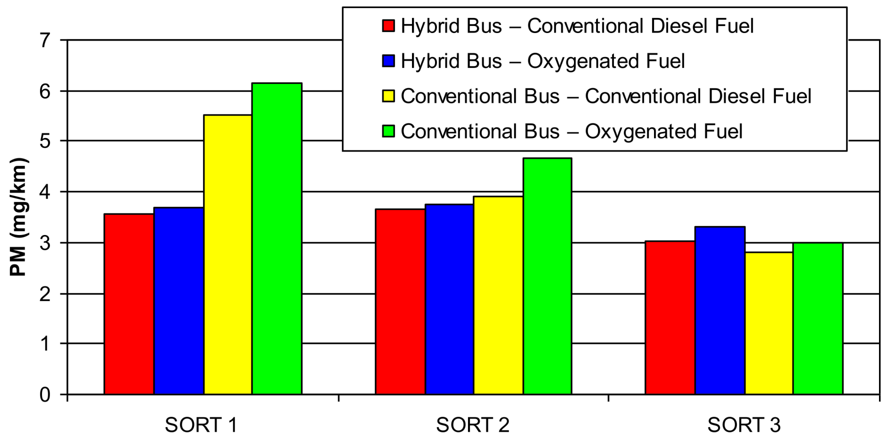


Figure 13. Comparison of PM emissions of serial hybrid and conventional city buses running on conventional and oxygenated diesel fuel, over the SORT cycles.

In terms of CO (Figure 10), the advantage of the hybrid bus and the beneficial effect of oxygenated fuel are clearly seen. However, it should be recalled that the hybrid bus was of a higher emissions standard (Euro VI) than the conventional one (EEV). There is definitely the highest CO emission for a conventional bus fuelled by diesel fuel in the SORT

1 cycle. In the mildest cycle, i.e., SORT 3, the differences in CO emissions for individual types of powertrains and fuels are small. An important observation is the large impact of the type of cycle on CO emissions by conventional bus, which is related to the different operating conditions of the engine in individual SORT cycles. In the bus with a series hybrid drive, the engine operating conditions are more stable, hence the small differences in CO emissions in individual SORT cycles are recorded.

In the case of HC emissions (Figure 11), the benefits of using hybrid propulsion are smaller than for CO. In addition, oxygenated fuel had little effect on the emissions from both types of vehicles. Road emissions decrease as cycle conditions are getting milder, but this is not a big change.

For NO_x emissions for all powertrain variants, a large impact of the cycle conditions on the emission level was noticed (Figure 12). NO_x emission was on average half lower for SORT 3 compared to SORT 1. This can be explained by the difference in engine load between the two cycles. For the SORT 1, the acceleration is more aggressive (between 0.62 and 1.03 m/s^2), whereas over the SORT 3, it is gentler (between 0.46 and 0.77 m/s^2). The influence of the use of oxygenated fuel on NO_x emission was insignificant. An important observation is that for NO_x, higher emissions were recorded for hybrid bus than for conventional bus.

Apart from the results for the conventional bus in the SORT 1 cycle, PM emissions were similar for all powertrains, fuels and cycles and amounted to 3 to 4 mg PM per kilometre of road (Figure 13). The highest PM emissions in the SORT 1 cycle should be combined with the most aggressive acceleration in this type of cycle, already mentioned in the discussion of NO_x emissions. No such dependence was found for the hybrid bus, which could be due to the more stable operating conditions of the internal combustion engine in the series hybrid drive system and/or more effective DPF (Euro VI) operation.

4. Conclusions

The Solaris Urbino 18 Hybrid bus used in the research was equipped with a serial hybrid drive system. It was noticed that for this bus, the differences between exhaust emissions in each type of SORT cycle (1, 2 and 3) were small, while for the conventional bus, exhaust emissions recorded in individual variants of SORT cycles were more differential. The reasons for this can be found in the characteristics of the series hybrid drive system, where despite the change in vehicle speed and power on the wheels, the operating conditions of the internal combustion engine change slightly. The exhaust gas aftertreatment systems, including SCR and DPF, also play an important role here. Both of these factors are the reason why the use of oxygenated fuel did not have a significant effect on the emission of any of the exhaust emissions components in any of the SORT cycles.

The reduction in emissions of some exhaust components was found when the Solaris Urbino 18 Hybrid bus was fuelled with oxygenated fuel during its actual operation on the bus line 76 of the Municipal Transport Company in Poznań. There was a reduction of CO emissions by ~50% and NO_x emissions by ~10%, almost identical levels of PM and HC emissions were observed and smoke opacity for both fuels. These are noticeable emission benefits, but rather not significant enough to justify the use of oxygenated fuel in the day-to-day operation of such a bus.

Analysing the obtained test results, it can be concluded that the influence of oxygenated diesel fuel on the exhaust emissions of modern city buses is quite favourable, although not as spectacular as in the case of older type vehicles. In modern vehicles, low exhaust emissions are due to the effective operation of advanced exhaust aftertreatment systems. Oxygenated fuels affect emissions by limiting the formation of toxic exhaust components during the combustion of fuel in the engine, thus their effect can be "masked" by a high-efficiency exhaust aftertreatment system. Nevertheless, the beneficial effect of oxygenated fuel may be, for example, less need to regenerate the diesel particulate filter, or to keep vehicle emissions low despite aging of catalytic converters and filters. Fuels also still have an important role to play in reducing greenhouse gas emissions. Renewable fuels, including biofuels and Power-to-Liquid technologies, have a potential in this respect. Thus, when deciding to apply oxygenated fuels, it is worth ensuring that oxygenates used are renewable components.

Author Contributions: Conceptualisation, M.K.; methodology, M.K. and P.L.; formal analysis, M.K. and M.W.; investigation, M.K. and P.L.; resources, M.K. and P.L.; data curation, M.K., P.L. and M.W.; writing—original draft preparation, M.K.; writing—review and editing, P.L. and M.W.; visualisation, M.K. and P.L.; supervision, M.K.; project administration, P.L. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by European Union from European Regional Development Fund through the National Centre for Research and Development (Narodowe Centrum Badań i Rozwoju)—research project within the Smart Growth Programme (contract No. POIR.04.01.02-00-0002/18-00).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

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