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Toxic Emission During Road Tests of Urban Bus

Paweł Magryta[1*], Łukasz Grabowski[1], Grzegorz Barański[1], Mirosław Wendeker[1]

[1] Department of Thermodynamics, Fluid Mechanics and Aviation Propulsion Systems, Lublin University of Technology, Nadbystrzycka 36, Lublin 20-618, Poland

* Corresponding author's e-mail: p.magryta@pollub.pl

ABSTRACT

The article presents the results of toxic emissions in road tests of an urban bus. The object of the study was the Mercedes Connecto city bus. The results of toxic emissions were recorded in real time while bus drives with the use of the Semtech Ecostar exhaust gas analysis system. The study involved a planned bus SORT 2 test cycle. During the tests, the fuel consumption and exhaust gases such as CO_2, CO, NO_x, HC, NMHC, and O_2 were recorded. The driving conditions in the study were constant (test cycles took place at the airport), exhaust gas temperature (hot engine) was also constant, etc. The results were based on average values from 5 test cycles for each test. The influence of electric load in the bus grid on the level of toxic emissions was measured. It has been proven that fuel consumption and CO_2 emissions increased, which means a change in the value of components of toxic emissions. This fact evident from the increased CO emissions and decreased O_2 emissions. Logically, the air-fuel mixture may have been enriched due to the increased demand for effective power generated by the engine crankshaft.

Keywords: SORT 2; emission; city bus; toxic emissions; electric energy.

INTRODUCTION

Vehicles, including city buses, are a significant source of air pollution, especially in urban areas. Many buses equipped with diesel engines are still in operation. The engines of these vehicles emit particulate matter, nitrogen oxides, hydrocarbons, carbon monoxide, and other gases and components. This has a significant impact on air quality, especially in urban areas and the morbidity of people exposed to these compounds. Road transport has become one of the greatest threats to civilization. Automotive air pollution is particularly associated with the costs borne annually by inhabitants of cities. Studies conducted in some European countries have shown that the number of victims of deadly automotive emissions is several times higher than the number of victims of accidents. The British have calculated that the social cost of 1 liter of diesel in the UK is £1. The data reported in the Lancet indicate that three air pollutants: particulate matter (PM), nitrogen dioxide (NO_2), and ozone (O_3) are responsible for 400,000 premature deaths per year in the EU, including about 70,000 directly related to nitrogen dioxide (NO_2). The health cost of 1 tone of nitrogen oxides in London has been estimated at £100,000, the cost of 1 tone of particulate matter is already £273,000 [1]. Therefore, research work focuses on how to reduce fuel consumption and thus the amount of toxic emissions emitted by a city bus, which was discussed in [2, 3] and [4]. The level of emissions depends on vehicle load, as described in [5] using the fuel consumption and fuel type method. The included results show that switching from diesel to CNG or LNG reduces GHG emissions by 4.8% and 8.1%, respectively. In one of the studies [6], the authors included the results of modelling the emission of toxic exhaust compounds depending on vehicle load. A similar approach was presented by [7], but there the results of actual measurements of buses equipped with diesel engines and CNG-fuelled engines were included. The measured concentrations of

NO_x and particulate matter under road conditions showed that road traffic is a decisive factor in creating areas with high pollutant concentrations.

Decarbonizing public transport is one of the goals of many countries [8]. The way to use buses equipped with electric powertrains and to reduce personal transport in urban areas was mentioned in [9]. Diesel-equipped city buses, however, still represent a significant share of the fleet in operation worldwide. The report by the International Association of Public Transport [10] states that city buses equipped with diesel engine power units still account for 50% of the surveyed population. Electricity is actually, one of the important energy consumption sourcesin a city bus. The total electrical output of alternators installed in a city bus can be as high as 8 kW because many electrical auxiliary devices such as ticket machines, cash registers, display screens, etc. are installed in this vehicle, and, air conditioning fans are at the same time a heavy load. As shown by [11] and based on our research, the consumption of this energy may reach 2000-3000 kWh per year, which translates directly into higher fuel consumption and additional emissions of greenhouse gases and toxic components. Urban traffic is characterized by an extremely variablepower train load so the level of exhaust emissions at junctions and stops is researched. . Results of such research were discussed in [12]. It wasdemonstrated that the method of exploitation in urban conditions is closely related to the level of emissions. Similar research, i.e. the measurements of emissions from two buses exploited in Rome were analysed in [13]. It was shown that the emission level is significantly affected by the average vehicle speed. Lower values of CO and NO_x were obtained for the vehicle moving with a higher average speed.

The impact of electric load on fuel consumption and how this consumption can be reduced by using alternative sources of electric energy in the form of photovoltaic panels are discussed in [14]. This paper describesthe possibility of using panels mounted on the roof of the bus It turns out that this solution made it possible to provide about 20% of the required electrical energy. As mentioned earlier, the increased fuel consumption to generate electricity results in an increased emission of exhaust components. The he analysed literature provides for no information about the influence of electric load in the bus on emissions of toxic components.

Testing the on-road emissions of toxic components from internal combustion city buses is an important part of assessing the impact of public transportation on urban air quality. [15] Two main types of tests are used: on-road (on-road) tests [16] and dynamometer (chassis dynamometer) tests [17].

Therefore, this paper contains the results of the research on the influence of electric load on emissions of toxic components obtained from the driving tests described by the SORT2 speed profile for several values of alternate load. This translated into increased engine loading. This study aims to determine how load on the electrical system can affect emissions of toxic componentsof a city bus.

TEST CONDITIONS

The toxic emissions tests were performed on an apron surface at a former military airportin Biała Podlaska,Poland. The airport has a 3,300 meter long main runway and a 2,700 meter long reserve runway.

The tests were designed to demonstrate the effect of increasing electrical load on the emission of toxic compounds during the test run. Each test was performed according to the SORT 2 driving test guidelines. The tests were performed in three stages:

- Test drive 1 with a load of 770 W,
- Test drive 2 with a load of 2050 W,
- Test drive 3 with a load of 3210 W.

The SORT 2 driving test was created by The International Organization for Public Transport (UITP) to measure fuel consumption. Many members of the UITP organization consider the SORT driving cycle a reliable method for comparing fuel consumption of different bus manufacturers in a call for bids. The first work on designing the SORT cycle began in the late 2000s, and the first official publication was issued by UITP in 2004. As a result, the cycle has become an important reference for the bus transport sector in evaluating fuel consumption. The SORT test procedure makes it possible to evaluate not only the engine but also the design of the entire bus [18, 19]. The duration of the SORT2 test is 189 seconds. The test consists of three stages. Each of them differs in the maximum speed achieved, which is 20, 40, and 50 km/h, respectively.

The basic characteristic values for this test are:
- distance: 0.92 km,
- proportion of idling time: 34.5%,
- average speed: 17.9 km/h,
- maximum speed: 50 km/h,
- maximum acceleration: 1.03 m/s^2.

The load was implemented through an additional energy dissipation system in the form of heat and light energy. Five runs were performed for each stage. All results presented are averages of these runs for each stage separately.

The research vehicle was a Mercedes Conecto LF bus (Figure 2) which is at the disposal of MPK in Lublin. Conecto LF is a 12-meter, low floor bus with a structure made of welded closed sections of stainless steel, able to accommodate 94 people (26 seats and 68 standing places). The engine is located in the tower, in the left rear corner of the vehicle. It is a OM 926 LA unit which is a standing inline 6-cylinder diesel engine with a maximum output of 205 kW (278 hp) and a displacement of 7.23 liters. The Euro IV emission standard is achieved through the use of BlueTec technology, i.e. the injection of AdBlue liquid in the system, allowing the reduction of NO_x content in the exhaust gases. A bus equipped with this engine consumes an average of about 39 litres of diesel fuel per 100 km. Drive from the engine is transmitted through a 4-speed automatic transmission Voith 854.3 (ratios: 1-5.3 2-1.43 3-1.0 4-0.7) and then to the drive bridge ZF AV-132 (ratio: 7.38) with the main gearbox mountedin the left wheel arch. The bus has an electronically controlled air suspension with a kneeling option. Per year, the bus consumes 31300 litres of diesel fuel.

Electric energy demand in the tested bus is satisfied by two alternators with a total maximum current of 200 A (vehicle electrical system, ticket punchers, monitoring, and displays) and an alternator with a capacity of 140 A installed in vehicles with air conditioning (Figure 1).

The bus was equipped with a real time data logging system based on a Compact Rio ncRIO 9024 measurement card by National Instruments. The software was also developed in the LabView environment. This made it possible to monitor and record the voltage (U) and current (I) in the electric system of the city bus. An HTR 300SB current transducer was used to measure the current. The transducer was mounted on the cable connecting the alternator to the battery. The diagnostic transmission of the bus (FMS Standard, Profibus network communication defined by DIN 19245) provided the following technical data: engine crankshaft speed, hourly fuel consumption, vehicle speed, and the position of the accelerator lever.

The bus was equipped with an exhaust gas analysis system that was powered by a generator on board. The analyser flow meter was mounted on the rear of the bus (Figure 2). The system was

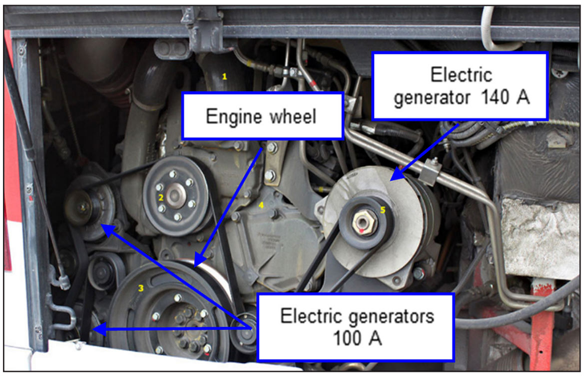

Fig. 1. Mercedes Conecto bus engine compartment with its alternators [20]

Fig. 2. Test vehicle

Fig. 3. Exhaust gas analyser fitted to the test vehicle

tightly mounted to the exhaust system of the city bus by using a flange connection (Figure 2). The exhaust gas samples collected by the flow meter were then transported to the exhaust gas analyser in the middle of the bus through the rear passenger door (Figure 3).

The tests were performed during a drive by means of the SORT 2 driving test. A single test lasted 183.9 seconds and consisted of three phases, i.e. acceleration, constant speed driving, and braking.

SEMTECH ECOSTAR FLUE GAS ANALYSER

The emission of toxic components of exhaust gases was tested with a Semtech Ecostar exhaust gas analyser (Figure 4). The exhaust gas emission analysis system by Sensors Inc. allows a continuous measurement of emissions of toxic components in driving and stationary conditions. It consists of Ecostar Semtech products and contains several individual modules, each of which has a specific functionality. These modules can be used as analytical devices for autonomic measurements or can be used as part of a fully integrated measurement package. Each module is designed to maintain high end analytical performance while operating in extreme test environments. The system offers optimum elasticity, performance, and ease of use during real-world testing and under harsh test conditions. It is capable of measuring toxic exhaust emissions by UN-ECE.R-49 and (EU) No. 582/2011 as well as CFR40 part 1065 and complies with ISO 9001-2000 and EN 14181:2004 [21]. The analyser has separate modules that briefly decribed below.

PDM module

The PDM (Power Distribution Module) distributes power (electricity) to each module. It can be connected to a 110–240 V AC power source or a DC power source such as a z-battery.

FEM module

The FEM (Fuel Economy Meter) module is a module responsible for measuring fuel consumption. It measures the flow of exhaust gases with a flow meter and the content of CO and CO_2 in the exhaust gases by the carbon balance method. It has a system for a automatic collection of a sample from exhaust gases. The dried and filtered gas sample passes through a nondispersive infrared analyser to measure CO, CO_2, and HC contents. The exhaust gas sample is additionally checked with a humidity sensor to eliminate indication errors due to changes in humidity. Additionally, the O_2 content in the sample is analysed using an electrochemical and paramagnetic oxygen sensor. The concentration of the tested toxic components and the exhaust gas flow rate can be continuously monitored . Additionally, the system analyses the value of exhaust gas pressure and temperature. The resolution of measuring CO is equal to 10 ppm and accuracy ±50 ppm in the range of 0–8% and CO_2 is equal to 0.01% and accuracy ±0.1% in the range of 0–20%.

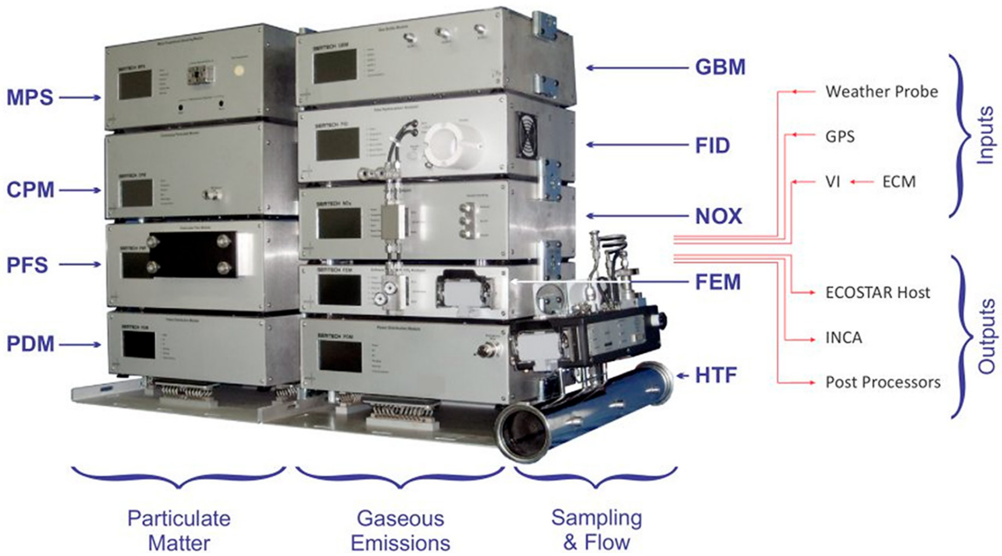

Fig. 4. Semtech Ecostar flue gas analyser [22]

NO_x module

The NO_X module measures NO and NO_2. It uses nondispersive ultraviolet (NDUV) sample analysis technology. In combination with the FEM module, it allows the analysis of the same sample taken from the exhaust gas. To avoid the influence of changes in exhaust gas temperature on the measurement, it is equipped with six separate temperature zones the sample passes through. Each zone is monitored for temperature values. Nondispersive ultraviolet (NDUV) sample analysis is based on spectroscopic absorption technology. Different ultraviolet wavelengths are used to measure the values of NO and NO_2 because these wavelengths are not affected by the presence of CO_2 or H_2O which do not absorb ultraviolet light. The resolution of measuring NO is equal to 0.3 ppm and accuracy ± 0.3% in the range of 0 to 3,000 ppm and NO_2 is equal to 0.3 ppm and accuracy ± 0.3% in the range of 0 to 500 ppm.

FID module

The FID (Flame Ionization Detector) module measures total hydrocarbons (THC) using a flame ionization sensor in a vacuum. The system is designed to minimize the temperature loss of the flue gas sample by heating all intermediate parts the sample will be taken from. The module has a freely calibrated measuring range of 0-90 and 0-30 000 ppm. The system has an additional heated filter and sample drier. The whole measuring and sample transport system is heated up to 191 °C. The module operates using additional hydrogen/helium fuel which is supplied from an external cylinder. The module mixes this fuel with filtered ambient air (by an additional catalyst) and the exhaust sample and then burns the entire mixture using a flame. This also burns hydrocarbons which create positive ionizing charges. These charges are then captured and measured by a negatively magnetized plate sensor. The accuracy of measuring THC is equal to ±0.3% in the range of 0 to 30,000 ppm.

MPS module

The MPS (Micro Proportional Sampling System) module is an exhaust flow dilution system for partial flow splitting, meeting the requirements of both US EPA CFR 40 part 1065 and ISO 16183 and may be used in combination with a FEM. It may operate as a proportional dilution module or as an autonomic dilution module. It is also suitable for use with the PFS particulate measurement module using gravimetric filters. An optional remote-controlled manifold can be easily fitted to the system. It has a touch screen that allows you to configure the system, view basic functions and online monitored data.

PFS module

The Particulate Filter System (PFS) module is a device that performs precise measurements of particulate matter using a gravimetric method. To achieve the required velocities on the filter surface corresponding to a wide range of flow rates, the filter holder uses an industry standard 47 mm filter container and conventional inlet and outlet cones. The system is controlled by a microprocessor which uses solenoid valves to introduce the sample through one of three filters, a so-called "bridge". Its optimized design is lightweight and compact, making it possible to carry out laboratory quality measurements in both field and stationary conditions. The particle filter system works directly with the SEMTECH-MPS and introduces the separated sample through an input from the bottom of the MPS to the top of the PFS. It has a touch screen that allows you to configure the system, view basic functions and online monitored data.

CPM module

The CPM (Continuous Particulate Measurement) module allows for continuous measurement of particulate matter using an ionization method. The module uses a technique by which clean air is ionized and mixed with a sample, causing the particles to become charged. When the charged particles exit the sensor, their charge is measured by an accurate electrometer. Thus, the CPM is a real time particulate measurement system that can be configured to measure particle number or mass. The module includes a Pegasor electric aerosol detector which can be used as a standalone analyser or integrated with the SEMTECH MPS and PFS modules to provide a complete measurement for both real-world and laboratory applications.

RESULTS

The results are summarized in three steps:

- In the first step, the fuel consumption and emissions of individual toxic compounds such

as CO_2, CO, NO_x, HC, NMHC, and O_2 in the unit [g/km] were presented. Energy usage factor f was introduced. The factor illustrates the quotient of fuel consumption or toxic emissions in grams between Test drive 3 and 1 and their respective electricity consumption.
- The second stage presents a comparison of the obtained results by calculating the average value kx of changes in the measured quantitieswhere x stands for fuel consumption, CO_2, CO, and NO_x, respectively.
- In the third stage, the SORT2 Driving Test was divided into parts corresponding to driving conditions: acceleration, constant, deceleration, and idle. The amount of toxic components in grams was counted as their sum from the three consecutive test drives separately for acceleration, constant, deceleration, and idle.

First step

Table 1 presents the fuel consumption and emissions of each toxic compound under the various test drives.

In order to compare all test drives in terms of fuel consumption and toxic emissions in relation to the generated electric power, the energy usage factor f was introduced. This factor was determined from the following formula.

$$f = \Delta m_{emi} \,/\, \Delta E_{elec}\,[\mathrm{g/kWh}] \tag{1}$$

The ratio illustrates the quotient of fuel consumption or toxic emissions Δm_{em} in grams between Test drive 3 and Test drive 1, per their respective electricity consumption ΔE_{elec} in kWh between Test drive 3 and Test drive 1. This comparison allows us to determine the increase in fuel consumption or toxic emissions for the increased amount of energy produced in the bus.

Second step

A comparison of the obtained results was made by calculating the average value k_x of changes in the measured quantities where x stands for fuel consumption, CO_2, CO, and NO_x, respectively. All the obtained data are shown in Table 3.

$$k_x = [[(x_2 - x_1) + (x_3 - x_2)]/2] * 100\% \tag{2}$$

Data x_1, x_2, x_3, are consecutive values of fuel consumption, CO_2, CO, NO_x. The factor was used only for the above values because the unambiguous effect of generated electric power was shown in this case.

An analysis of the measurement results showed the effect of additional electric power in the bus on the load on the internal combustion engine. In the case of fuel consumption, proportionally higher values were obtained for the successive electric loads. The change in carbon dioxide emissions, which increased by more than 100 g/km, is analogous. This clearly shows that each

Table 1. Toxic compound emissions during the test drives

Parameter	Fuel consumption [g/km]	CO_2 emission [g/km]	CO emission [g/km]	NO_x emission [g/km]	HC emission [g/km]	NMHC emission [g/km]	O_2 emission [g/km]
Test drive 1	366.781	1160.678	1.754	14.738	0.093	0.091	2532.204
Test drive 2	388.400	1229.697	2.066	15.384	0.096	0.094	2550.886
Test drive 3	408.531	1294.731	2.163	16.363	0.094	0.092	2471.321

Table 2. Energy usage during the test drives

Parameter	Fuel consumption	CO_2 emission	CO emission	NO_x emission	HC emission	NMHC emission	O_2 emission
Energy usage [g/kWh]	263.084	844.716	2.576	10.243	0.0047	0.0046	-383.647

Table 3. Calculation parameters

Parameter	Fuel consumption [g/km]	CO_2 emission [g/km]	CO emission [g/km]	NO_x emission [g/km]	HC emission [g/km]	NMHC emission [g/km]	O_2 emission [g/km]
Consecutive values x_2-x_1	6%	6%	15%	4%	3%	3%	1%
Consecutive values x_3-x_2	5%	5%	4%	6%	-2%	-2%	-3%
Average value k_x	5.5%	5.5%	9.5%	5%	–	–	–

kilowatt-hour of electricity produced on board the vehicle generates an increased demand for the energy contained in the fuel. A 5% increase was shown in fuel consumption and carbon dioxide emissions.

A similar trend was obtained when carbon oxygen emissions were examined. However, in this case, the increase contributed 10% sequentially. The test was performed in each case of electric load with the same vehicle speed profile over time. This is because the increased load on the compression ignition engine resulted in the need to burn a richer air fuel mixture to achieve the same vehicle speed.

NO_x emissions also depend on the power of electricity generated on board. It was found that there is an average 5% increase in NO_x emissions.

The analysis of hydrocarbon emissions did not show a clear trend in the influence of generated electrical power. For HC and NMHC, there was an increase in emissions in the second variant of electric load. However, for the third value of electric power, values similar to those obtained in the test conducted at the lowest electric load were obtained. The negative values seen in table 3 for HC and NMHC for Test drives 3 and 2 are the result of a reduction in these parameters in test 3 compared to test 2. Therefore, in this regard, it is not possible to clearly say how hydrocarbon emissions change as a result of increasing electrical power generated by the alternators.

The mass of oxygen in the exhaust gas decreased slightly in the driving test at maximum electrical load. The increased demand for effective engine power resulted in an increased amount of fuel in the mixture feeding the engine, which, in turn, translated into a reduced amount of oxygen in the exhaust gas (expressed as a negative value), since the amount of air supplied to the engine was the same in both cases.

Third step

The SORT2 driving test was divided into parts corresponding to driving conditions: acceleration, constant, deceleration, and idle. The division is shown in Figure 5.

The amount of toxic components per unit g was counted as their sum from three consecutive test drives separately for acceleration, constant, deceleration, and idle. The standard deviation, on the other hand, is the average of the three deviations for the aforementioned tests for 5 runs for each test.

The results of the calculations carried out as part of the analysis are included in Figures 6-12. These are the calculated fuel consumption and mass values of the various emitted compounds contained in the exhaust gas. The results are rearranged in the form of bar graphs for the successive operating states (acceleration, constant, deceleration, and idle) and three values of electrical loads.

The graphs showing the fuel consumption and CO_2 emissions are similar in shape and differ only in scale because the CO_2 emissions are proportional to the fuel consumption. Negligible differences may be due to the mass balance of the combustion process and the changes in CO, HC, and NMHC emissions.

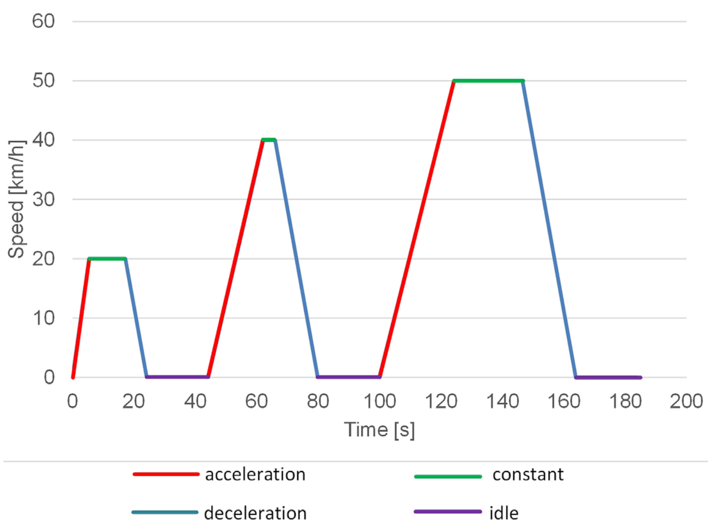

Fig. 5. SORT2 driving test division

The fuel consumption results confirm that increasing electrical load increases fuel consumption in every vehicle load condition. Only in deceleration there was no clear increase in fuel consumption due to the increased power demand during the alternator drive. This may be because in deceleration part of the power to drive the alternators may come from kinetic energy stored in the mass of the bus.

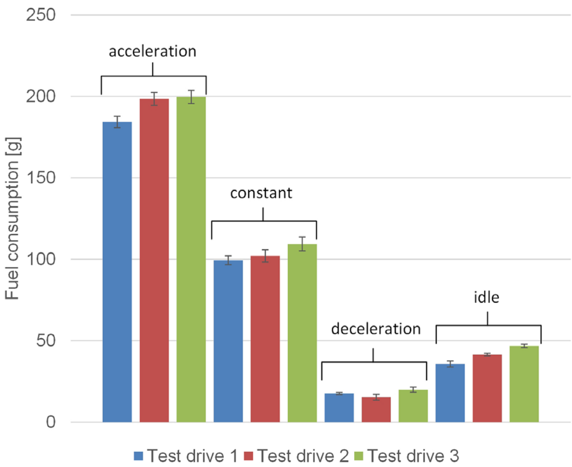

Fig. 6. Fuel consumption

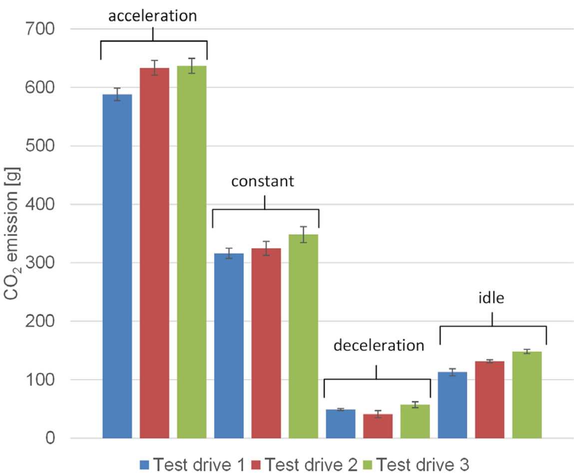

Fig. 7. CO_2 emissions

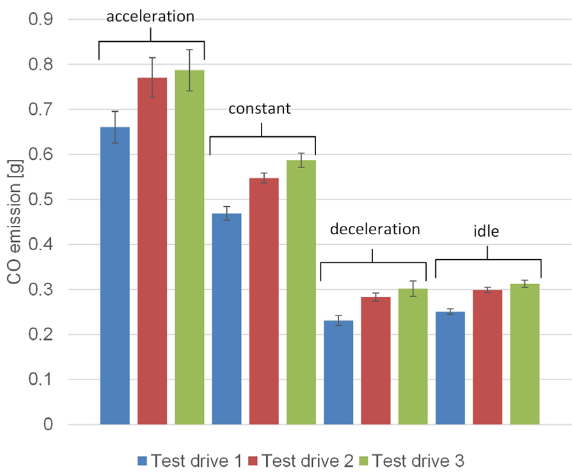

Fig. 8. CO emissions

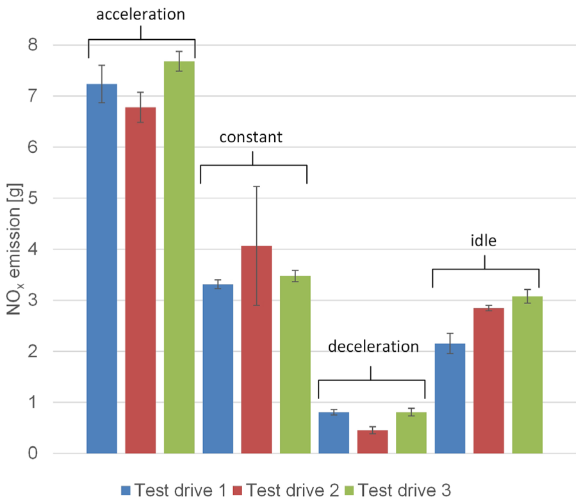

Fig. 9. NO_x emission

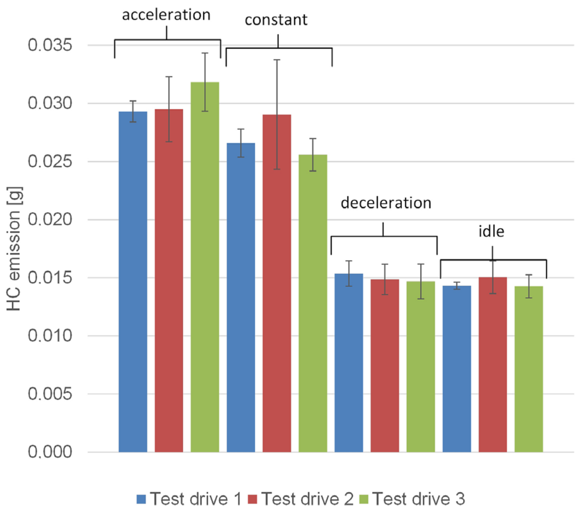

Fig. 10. HC emissions

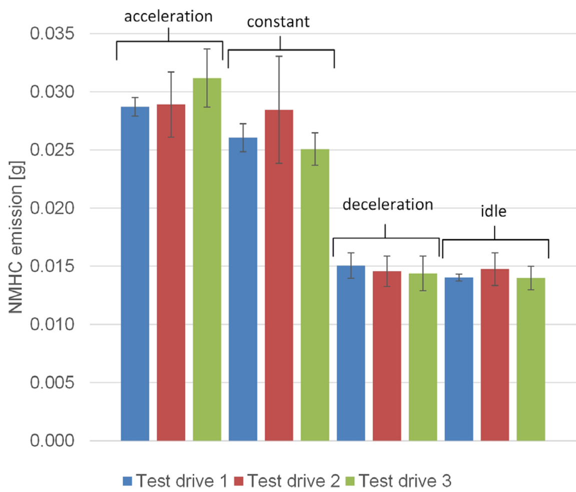

Fig. 11. NMHC emissions

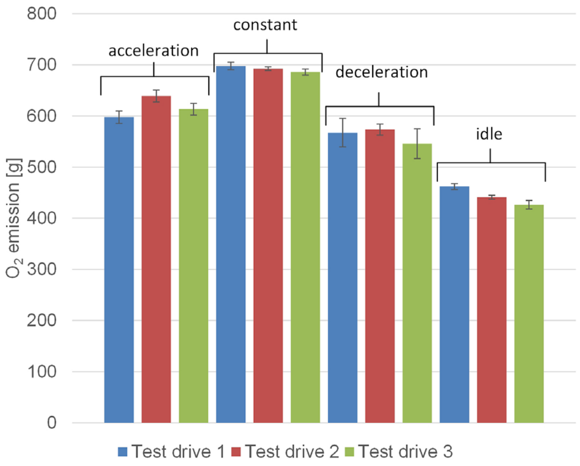

Fig. 12. O_2 emissions

In the case of CO, the effect of the electrical power generated by the alternator on the emitted mass of this compound during the SORT2 driving test was demonstrated. There was an increase in CO emissions in each of the operating condition cases (acceleration, constant, deceleration, and idle). This can be related to the fact that the mass of emitted O_2 decreased. This means that the drive of the alternators causing additional load on the engine enriched (decrease in lambda) the average fuel-air mixture.

The resulting NO_x masses are not clearly related to the electrical power generated by the alternators. Only in the case of idling there was an increase in NO_x emissions. Also, in the case of the HC and NMHC emissions, an additional electrical load did not directly affect the emissions of these compounds.

CONCLUSIONS

The article presents the results of a study of how the value of electrical power generated on board by alternators of a city bus influences fuel consumption and emissions of toxic components. SORT2 driving cycles were used in the study to guarantee the road conditions to be properly reproducible with different electrical loads on the alternators. The test object was a Mercedes Conecto city bus. The test results were analysed in detail.

In the first step, the fuel consumption and emissions of individual toxic compounds such as CO_2, CO, NO_x, HC, NMHC, and O_2 in the unit [g/km] were analysed. A special factor was proposed to determine the weight of fuel and exhaust compounds per kWh of electricity. It was shown that producing 1 kWh of electrical energy requires a consumption of about 260 g of fuel and results in increased emissions of all measured compounds. Reduction was observed in the case of oxygen only due to burning richer mixtures during increased electrical load.

The authors proposed a comparative analysis that calculated the k-index which is a percentage of changes in fuel consumption and toxic emissions. The results were converted in relation to the driving cycle, i.e. in grams per kilometre travelled. A 5% increase in fuel consumption of carbon dioxide and NO_x emissions was shown. The largest increase was registered for carbon monoxide emissions, which may be due to the reduced value of the lambda coefficient. For hydrocarbons emissions, the results were inconclusive.

The final stage of the work was a detailed analysis of the impact of electrical load and toxic emissions in the various stages of the SORT2 cycle. It was proposed to divide the SORT2 cycle into four types of operation (acceleration, constant, deceleration, and idle). Each of them corresponded to different loads on the internal combustion engine. It was shown that in all four stages (operating states) there is an unambiguous increase in the fuel consumption, $CO_2$and CO emissions. However, in the case of the HC and NO_x emissions the effect of electric load on the emissions of these compounds was not unambiguous.

Summarizing the analysis, it should be concluded that the value of the electrical power generated by the alternators has a significant effect on internal combustion engine loads in a city bus. Increased fuel consumption and increased CO_2 emissions were recorded and stand for a change in the value of toxic emissions. This fact is evident from the increased CO carbon monoxide emissions and decreased O_2 emissions and implies an enrichment of the air-fuel mixture resulting from the increased demand for effective power generated by the engine crankshaft.

Acknowledgements

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Nomenclature

PDM – power distribution module
FEM – fuel economy meter
FID – flame ionization detector
MPS – Micro Proportional Sampling System
CPM – Continuous Particulate Measurement
PFS – Particulate Filter System
CO_2 – carbon dioxide
CO – carbon oxide
NO – nitrogen oxide
NO_2 – nitrogen dioxide
NO_x – nitrogen oxides
HC – hydrocarbons
NMHC – nonmethane hydrocarbon
O_2 – oxygen

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