

Pollutant emissions analysis of a hybrid drive bus in a SORT 2 test

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Abstract. The paper presents the results of emission tests of a city bus equipped with a series hybrid drive. The measurements were performed in accordance with the current guidelines of the standardized SORT 2 test (Standardized On-Road Test Cycles 2) reflecting the typical urban driving conditions. The analysis includes gaseous compounds (CO₂, CO, THC and NO_x). SEMTECH DS mobile device categorized as portable emissions measurement systems was used in the research. The test vehicle operating conditions were evaluated in relation to the operating parameters variability and the drive system. In addition, a comparison of the fuel consumption and travel velocity recorded during the test cycle have been shown. The research object was an 18-meter long city bus with a 6.7 dm³ displacement engine, meeting the current emission standards. The article discusses the issue related to the type approval of buses, which belong to the heavy vehicles group, but they are characterized by very specific operating conditions. Based on the obtained data, the ecological indicators of the tested vehicle were determined and compared with the limits in force in the current Euro VI standard.

1. Introduction

In 2008, the European Commission adopted Directive 2008/50/EC on air quality in Europe. It defined the limit of PM10 concentration, as not to exceed 50 µg/m³ during the day (this limit can be exceeded no more than 35 times in any given year) and a yearly average limit of 40 µg/m³ [9]. The Directive also sets a NO₂ yearly average concentration limit of 40 µg/m³. In order to improve the quality of atmospheric air in large urban agglomerations the European Commission allows the creation of special LEZ (Low Emission Zone) ecological areas. In these zones the traffic of motor vehicles will be significantly reduced. Only vehicles that meet the newest emission standards can travel within them. In addition to urban agglomerations, it is also possible to cover low traffic areas with high emission such as main bypass routes, highways and expressways with these zones. Figure 1 shows a map of the existing LEZ zones in the European Union. The LEZ restrictions apply mainly to heavy vehicles and public transport buses with a permissible total weight over 3,500 kg. However, there are zones that also regulate PC passenger traffic and NRMM category vehicles. In these zones, the emission criterion is divided into three main categories [6, 11]:

- 1) the vehicle meets the set Euro and Stage emission standard,
- 2) the vehicle is equipped with a functioning DPF device,
- 3) the vehicle is equipped with a functioning DPF and SCR devices.



The Euro emission class is usually determined based on the first registration date of the vehicle – for example, for a vehicle registered in 2005 it is expected to meet the Euro 4 standard. If additional DPF and SCR catalytic systems are used in the exhaust system, it is necessary to have special certificates for these systems that comply with legislative provisions valid in a given LEZ. There is no LEZ in Poland, but recently works have been underway to create such areas in major agglomerations. This is related to the published report of the European Environmental Agency (EEA) regarding the state of air quality in the European Union. In the top 10 cities with the highest air pollution, there were 6 Polish cities in which the daily PM₁₀ concentration limit was exceeded [3, 4]. Kraków is the worst of them, where the limits were exceeded for 150 days in a year, in Nowy Sącz this was 126 days, in Gliwice and Zabrze 125 days, in Sosnowiec 124 days, and in Katowice 123 days. The biggest problem for air quality in our country is the excessive concentrations of PM₁₀ and PM_{2.5} as well as benzo(a)pyrene (B(a)P). On the national scale, in 2010–2013, the limits of PM₁₀ in the air were exceeded in more than 75% of all zones in which air quality is assessed, and in the case of benzo(a)pyrene in approx. 90% of these zones. In 2009–2012, the main cause of PM₁₀ air pollution (between 82 and 92.8% of it) was due to the so-called low emissions sources, such as domestic stoves and local coal-fired boilers, where combustion takes place in a highly inefficient way. Other causes include pollution from transport (between 5.4 and 7%) and industrial pollution (1.8 to 9%). However, other local trends can also be found. In Warsaw, for example, transport pollution accounted for 63% of all pollutants found in the air. As the Supreme Audit Office notes, failure to meet the air quality standards set out in the EU CAFE Directive may have severe financial consequences for our country.

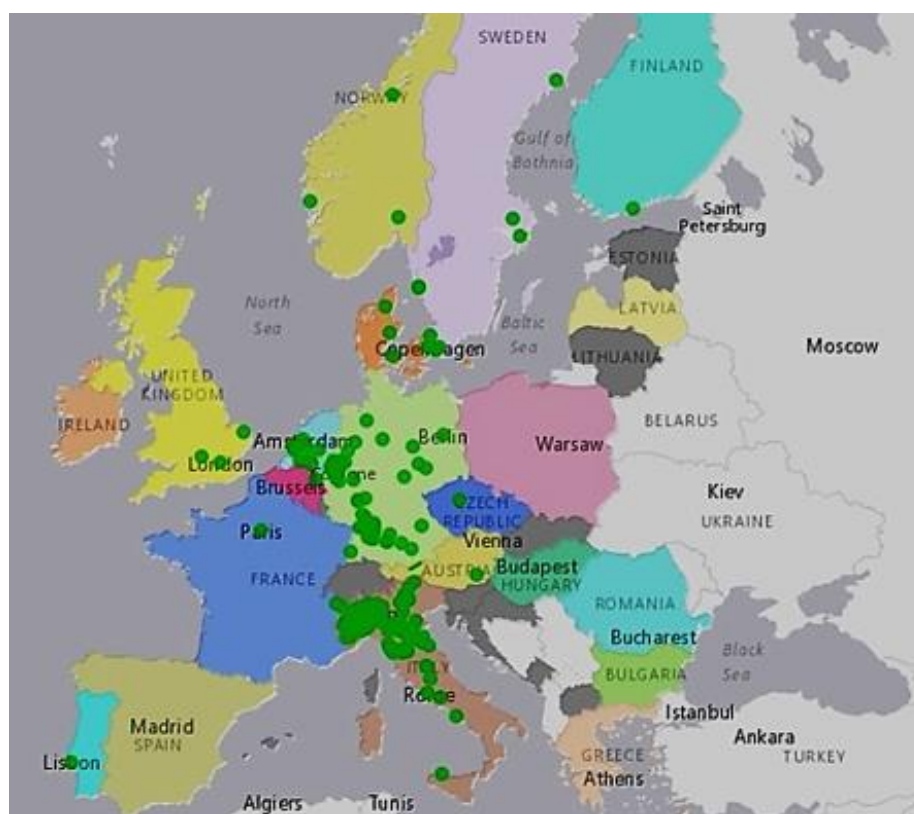


Figure 1. Areas with low emission zones (LEZ) in Europe – marked with green dots
[www.urbanaccessregulations.eu.]

The increasing population of the largest urban agglomerations in the world and the related increase in the number of used vehicles has become a determining factor for introducing innovative solutions in the public transport sector – Intelligent Transport Systems (ITS). It is a combination of information and communication technologies with transport infrastructure and vehicles positively affecting the way vehicles are used, and thus obtaining ecological and economic benefits [4, 7, 12].

The implementation of systems using the ITS methods contributes, among others, to [8]:

- a) reduction of transport infrastructure expenditures, obtaining the same effects of improving the system efficiency, as in the case of construction of new road sections (by 30–35%),
- b) reduction of travel times and energy consumption (by 45–70%),
- c) reduction of CO₂ emissions (among others due to the reduced number of vehicle stops and improved traffic flow),
- d) reduction of the road fleet management costs,
- e) reduction of costs related to maintenance and renovation of the road surface,
- f) improving road safety (reducing the number of accidents by 40–80%),
- g) improving the travel comfort and the road conditions for both the drivers and pedestrians,
- h) increase of economic benefits in the region (improvement of the economic situation),
- i) increasing capacity of transport networks elements without adding new road sections (by ~22%).

One of the basic ITS solutions is the use of BRT (*Bus Rapid Transit*) systems, which consists of designing a special infrastructure, which will be used by buses with increased length and permissible number of transported passengers. For this reason, the article presents the results of pollutant emissions investigations of urban bus with a hybrid drive used as the basis for the development of a vehicle intended for RTD systems. The measurements were made in the SORT 2 drive test, which reflects urban driving conditions.

2. BRT systems analysis

The road infrastructure for BRT systems is designed in such a way that only city buses can move along it, and it is integrated with major city transport hubs. Therefore, it eliminates the impact of road congestion on the transport operations carried out by city buses, which leads to an increase in the efficiency of transport services offered compared to conventional bus lines. First such system was developed and implemented as far back as in the 70s of the last century in the Brazilian Curitiba. Currently, BRT solutions are used in over 100 cities worldwide. In recent years, increased popularity of these types of systems has been observed in European countries. For this reason, many automotive companies not only offer dedicated public transport buses, but also participate in the design of the entire road infrastructure [1, 7, 14].

Very significant is the fact that the development of BRT systems is an investment that requires significantly less financial and infrastructure investments. In practical terms, the average cost of building an urban railway is 141% higher than for constructing the BRT system per 1 passenger-kilometer. The investment implementation time also favors the BRT solution. As an example, one can cite Bangkok, where two communication investments were made. First was a commissioned 426 km BRT network, and the second was a 7 km underground connection. It should be emphasized that the construction cost for both investments was similar. Thus it can be observed that BRT systems are becoming increasingly more commonly used solutions of Intelligent Transport Systems in developing urban agglomerations around the world [1, 14].

Up to date around 50 cities worldwide applied BRT systems (to varying degrees), and about 100 cities are planning to apply them soon. Volvo Buses is a company that intensely promotes this type of systems in the world. It helped develop the first fast bus system in Curitiba (Brazil). Currently, BRT systems are introduced in such cities as: Bogota (Colombia), Mexico City (Mexico), Göteborg (Sweden) and Santiago (Chile). The average time of launching the fast bus communication system is 12–18 months. Thanks to the BRT system in Bogota, it was possible to reduce fuel consumption of public transport by 47%. The emission of nitrogen oxides were reduced (by 65%) and the emission of solid particles decreased by 75%.

3. Research methodology

A public transport bus with a length of 18 m and a hybrid drive with a serial configuration was used for the tests (Table 1). It was equipped with a combustion engine with a displacement of 6.7 dm³ and a power of 233 kW. It generated a maximum torque of 1182 N·m in the engine speed range of 1150–1400 rpm and met the Euro VI emission standard.

In the SORT 2 test drive cycle, a PEMS type mobile device – Semtech DS from Sensors Inc. – was used to measure the pollutant emission from the public transport bus, which is a unique combination of measurement and registration of the following parameters:

- CO and CO₂ concentration (NDIR – Non-Dispersive Infrared), NO_x = NO and NO₂ (NDUV – Non-Dispersive Ultraviolet), HC (FID – Flame Ionization Detector), O₂ (electrochemical sensor);
- thermodynamic parameters of exhaust gas (mass flow rate, temperature, pressure) – a flow meter using a Pitot tube;
- ambient conditions – atmospheric pressure, temperature, humidity;
- position and velocity of the vehicle – GPS system;
- data from the vehicle diagnostic network data transmission protocol CAN SAE J1939/J2284.

In the performed tests, the Semtech DS main unit was placed inside the bus and secured against possible uncontrolled displacement (figure 2). A 4-inch diameter flowmeter was attached to the vehicle body to measure thermodynamic parameters of the exhaust gas, the device was tightly connected to the engine exhaust system. A GPS positioning system and a sensor of atmospheric conditions were placed on the vehicle roof, which were connected to the device main unit (blue lines in figure 3). The connection to the diagnostic network of the bus was achieved via a special module for data transmission using the SAE J1939/J2284 protocol dedicated to HDV category vehicles.

Table 1. Test vehicle technical data

Parameter	Value
Vehicle type	City bus category M ₃ class I and II
Vehicle length	18 m
Ignition system	Compression ignition
Number/layout of cylinders	6 in-line
Displacement	6.7 dm ³
Max. power	233 kW at 2300 rpm
Max. torque	1182 N·m at 1150–1400 rpm
Emission standard	Euro VI

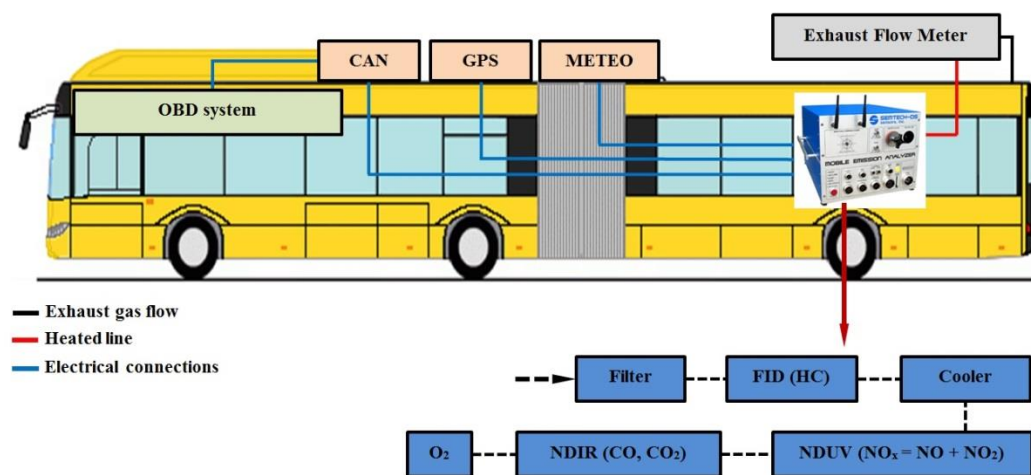


Figure 2. Diagram of the Semtech DS mobile device location in the tested buses

The exhaust sample was taken for analysis from the flow meter and transported by a heated conduit (red line) maintaining the temperature of ~190°C. This was to prevent HC condensation on the walls of the conduit. Then, after passing through the filter, the sample passed to the FID analyzer, where the HC concentration measurement was performed. After cooling to 4°C, the exhaust sample is directed to the NDUV and NDIV analyzers. There, the concentrations of NO_x = (NO and NO₂) as well as CO and

CO₂ were measured. At the very end, the O₂ concentration was measured using an electrochemical sensor. Control and monitoring of the Semtech DS instrument was carried out by a portable computer connected to the main unit via a wireless network. The device has the ability to communicate using a local area network connection. In this research, this form of communication was not used.

In addition to type approval tests, where the exhaust emissions from the bus engine are tested while they are equipped with the exhaust gas aftertreatment system on the engine dynamometer, whole vehicle tests are also carried out on a chassis dynamometer or in road conditions [10]. The development of this type of tests is justified because they provide the possibility of assessing energy consumption for a given vehicle group in real operating conditions. In the case of city buses, the measure of the drive system energy consumption is the fuel consumption, which is the main operating cost for a vehicle operator. UITP (International Association of Public Transport) has developed the SORT (Standardized On-Road Test Cycles). The SORT drive tests consist of long drive cycles, and those of repeating modules, so that the vehicle driver can achieve a high repeatability of subsequent drives after stabilizing their driving style. The basic drive cycle module is described by the average drive velocity, the route length and the travel time. These parameters form a velocity that is characteristic for a given route, including stopping at stops and at traffic lights, starting from a stop and driving at a constant velocity. SORT 2 – Easy Urban selected for this research and discussed in the article reflects the operating conditions of a typical urban route (figure 3).

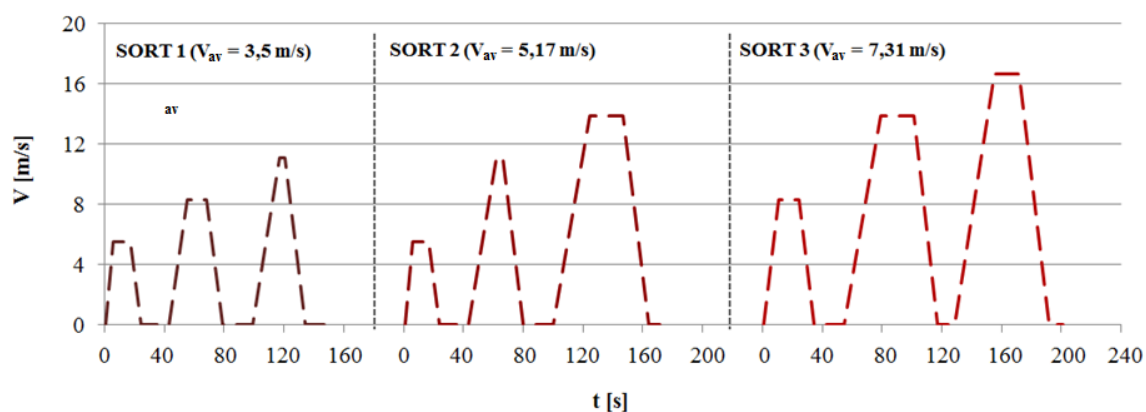


Figure 3. SORT drive test velocity [13]

Performing measurements in SORT drive tests requires adhering to many requirements, such as: using a special measuring road section and road surface, the temperature was in the range of 0–30°C, and the air humidity did not exceed 95%. In the analyzed case, the study used a vehicle in which the energy necessary to travel was provided by an internal combustion engine powered by diesel fuel. The procedure requires maintaining all of the initial measurement conditions set out in the SORT-2009, which requires switching off all auxiliary devices, i.e. heating, air conditioning, ventilation, displays, Wi-Fi, video recording, ticket checking devices, etc. with the exception of these systems, which are necessary for the proper operation of the vehicle, i.e. the steering system, pneumatic system, ABS, engine cooling system, the retarder, battery cooling system, etc., as stated in R 101, § 1.3.1 and 1.3.2. In order to determine the fuel consumption, three SORT test cycle measurements were performed. The test was carried out on a straight test track (airport runway), requiring repetition of the basic cycles in each direction so as to negate the effect of the wind/slope of the test track, etc. The basic driving cycle for SORT 2 covers a length of 920 m, and it was performed twice in each direction. A two-way test in two directions on a straight track gave a test section of one drive of 3,680 m. In order to obtain the value for one SORT test, the above mentioned tests were carried out three times, which allowed to determine the average of the three results so that the condition of good convergence of these results was maintained, which resulted in a measurement drive section length of 11,040 m. The battery charge status before and after the test was the same and the change in the state of charge of Net Energy Change Variance batteries after test was close to 0 in accordance with SAE J2711 [13].

4. Results

During the hybrid bus emission tests in real operating conditions, 16 repetitions of the standardized SORT 2 test drive cycle were performed. All tests were performed by the same qualified driver, and the drives were made in accordance with the UITP guidelines. Data regarding the obtained vehicle velocities were recorded from the on-board CAN diagnostic system (using the SAE J1939 protocol). They have been verified with the measurement made by the GPS device. Figure 4 presents randomly chosen velocity characteristics of the test object from test drives no. 1, 4 and 8. These are complemented by: the reference test velocity curve and the average velocity characteristic calculated from all the performed tests. The presented data confirmed that repeatability in subsequent measurement tests was obtained. This is also evidenced by the determined average velocities, which for the samples were respectively: $V_{P1} = 5.26$ m/s, $V_{P4} = 5.27$ m/s and $V_{P8} = 5.24$ m/s. The assumed average velocity of the road test SORT 2 is 5.12 m/s, while the average of all completed trips was at 5.26 m/s. The largest differences between the test results and the reference velocity occurred for the constant velocities and braking process in the third test trapeze – this was mainly related to the bus inertia and the driver's driving style.

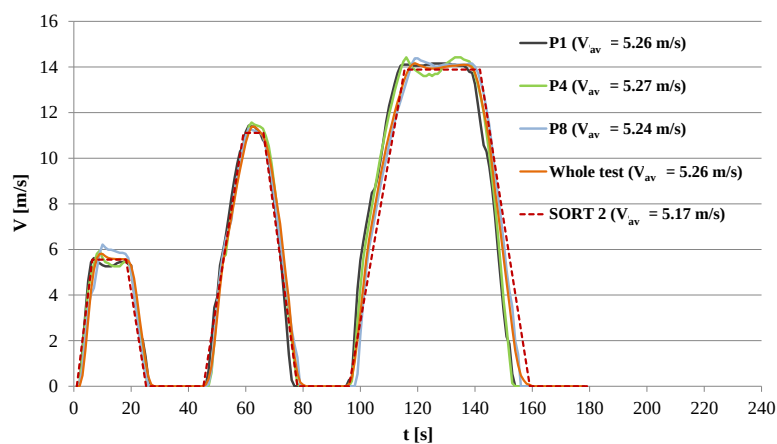


Figure 4. Test vehicle velocity characteristics in selected drives (P1, P4, P8) and average velocity from all tests in the standardized road test SORT 2 supplemented with a reference curve

Using the recorded velocity values in selected drives, determination coefficients were calculated taking into account compliance in time (figure 5). In addition, the formula of the obtained linear dependence is presented (all data was provided with accuracy of up to three significant digits). The

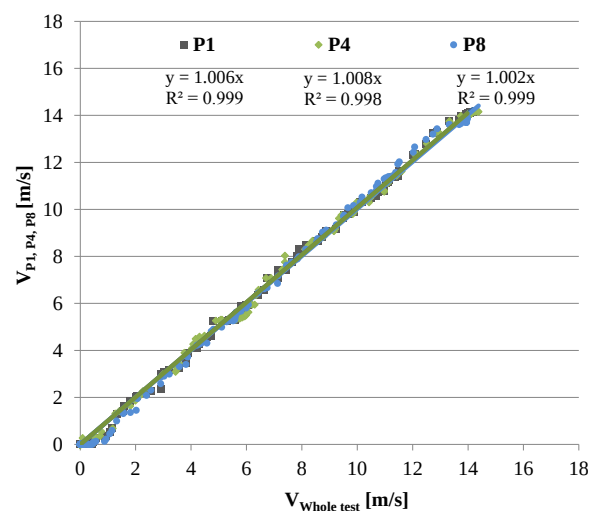


Figure 5. Comparison of the test vehicle velocity in selected samples (P1, P4, P8) of the SORT 2 road test with the average velocity from all tests taking into account its compliance in time

considerations include three samples marked as previously P1, P4 and P8. They were compared with the average drive velocity calculated for all tests. The results comparison made it possible to find the determination coefficients, which were all in the range of $R^2 = 0.998\text{--}0.999$. It was thus assumed that one sample will be selected to analyze the bus operating parameters and the drive system operation in the SORT 2 road test, which should be representative for the entire test.

The vehicle movement analysis was supplemented by the operating time density characteristics of the test vehicle being determined in relation to the established velocity and acceleration ranges (figure 6a). Due to the similar velocity characteristics in the tests and a high coefficient of determination value, only one characteristic of a selected representative drive was presented. The largest share of 27.2% in the drive was for a stationary vehicle. The theoretical expected value for the SORT 2 test is 30%, so the discrepancy is less than 3%. The distribution of operating parameters covers a wide range of velocity and acceleration values, with the highest values not exceeding 6% – the point defined by the interval (0 m/s; 2 m/s) and $\langle -0.8 \text{ m/s}^2; 0 \text{ m/s}^2 \rangle$. In the vehicle velocity range (6 m/s; 16 m/s) for acceleration (0 m/s²; 0.8 m/s²) the operating time density was 22.5%, whereas for the range $\langle -0.8 \text{ m/s}^2; 0 \text{ m/s}^2 \rangle$ it was 19.2%. The recorded acceleration values of less than -0.8 m/s^2 are due to the fact that the vehicle's movement did not run exactly along the assumed trajectory of the test, in subsequent profiles stronger braking of the bus occurred. The approximately symmetrical distribution of the operating parameters relative to the constant velocity results from the test drive character (successive trapezoids are symmetrical). The total share of driving at constant velocity (excluding vehicle stop) was 2%. As previously indicated, it resulted from the vehicle inertia and the specificity of the driver's actions.

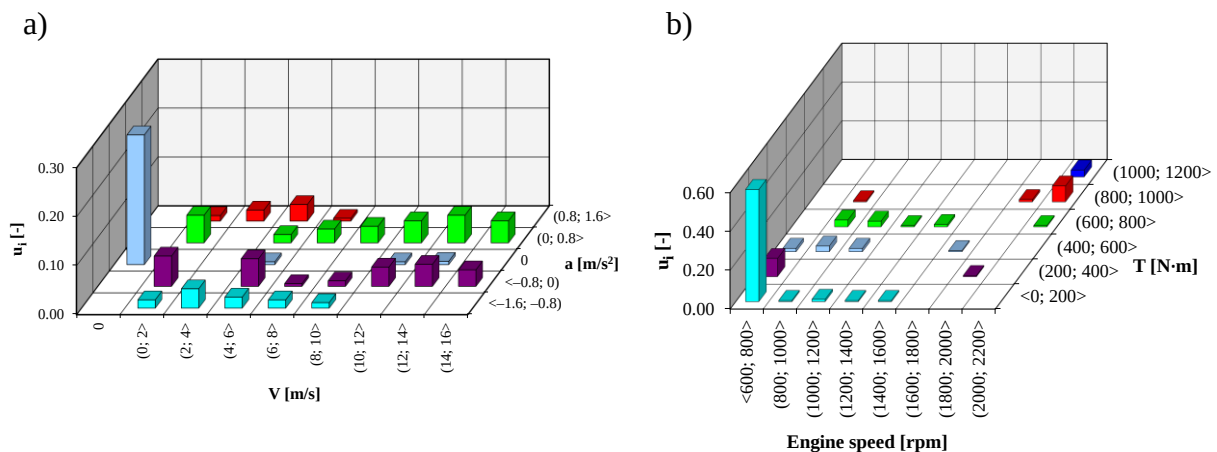


Figure 6. Test vehicle operating time density characteristics in the standardized road test SORT 2 in the following parameters: a) velocity and acceleration of the bus, b) engine speed and load

Using the data obtained from the CAN diagnostic system, the operating time densities of the internal combustion engine in the torque and engine speed ranges were determined (figure 6b). The largest operating time share equal to 57.8% occurred in the lowest engine speed range of $\langle 600 \text{ rpm}; 800 \text{ rpm} \rangle$ at loads not exceeding 200 N·m. The use of a hybrid drive and obtaining a proper degree of cooperation of its main components with the engine allowed obtaining a limited operating parameters variability range. This is very beneficial in terms of pollutant emissions, because the largest emission factors occur in transient states. For engine speeds greater than idling, with loads up to 200 N·m, the total share of operating time was 2.9%. For the range described by the values (600 rpm; 800 rpm) and (200 N·m; 400 N·m) the obtained share was 9.4%. In the speed range above 2000 rpm at loads exceeding 800 N·m, an average operating time density of 5.8% was determined in individual ranges. In individual ranges of the operating time density characteristic, the share did not exceed 3.3%.

Using the obtained exhaust emission characteristics and the drive system parameters along with the velocity characteristic, a comparison of the results was made (figure 7). In accordance with the adopted test procedure and measurement delay of individual analyzers, multi-aspect time

synchronization was performed – data sets were compared with each other by overlapping peaks. The exhaust emission is closely related to the vehicle operating parameters – for all analyzed compounds the highest instantaneous emission values occurred during acceleration. The advanced exhaust gas aftertreatment systems, characterized by a high conversion rate, had a significant influence on the obtained results. The alternative drive when accelerating uses energy not only from the internal combustion engine, but also from the energy storage devices. This way the combustion unit is put under less load so that incomplete and partial combustion is limited. In addition, the design of the engine itself and the control strategy used also influenced the exhaust emission characteristics. The obtained results are characterized by much smaller values compared to the bus of the same class that meets less stringent emission standards, e.g.: [5, 10].

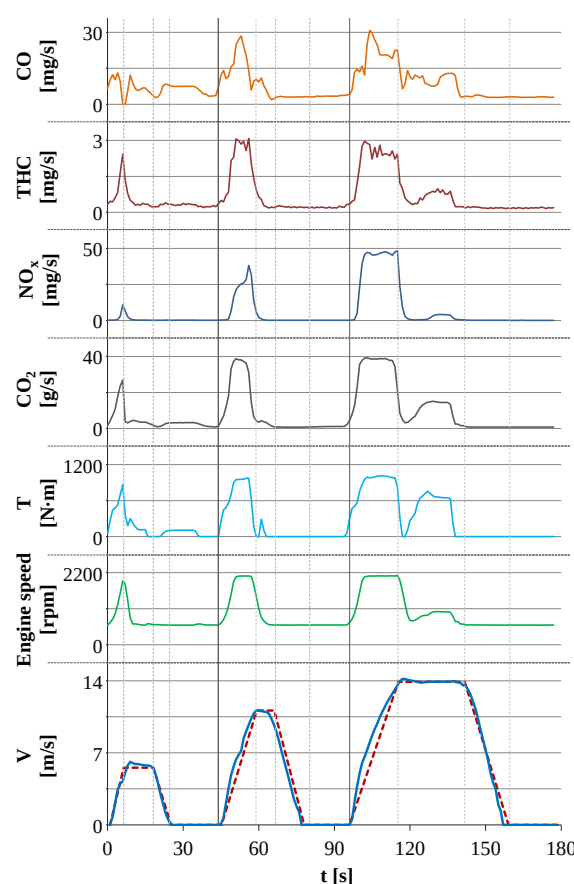


Figure 7. Test vehicle velocity characteristics, engine speed, torque and exhaust emissions: CO, THC, NO_x, and CO₂ recorded during tests in the standardized road test SORT 2

The highest instantaneous CO emission of 29.8 mg/s occurred during rapid acceleration in the third test profile. In contrast, for THC the highest value of 3.1 mg/s was obtained in the second test profile while driving at a constant velocity. The exhaust gas recirculation system and the SCR catalytic reduction system were used to reduce the NO_x emissions of the vehicle. The SCR system conversion rate depends primarily on the temperature and exhaust gas mass flow rate – at a higher flow rate the conversion rate is lower. The NO_x emission is closely related to the vehicle load, therefore the highest values of approx. 47 mg/s were observed for the third test profile. The emission of CO₂ is closely related to the fuel consumption, so its characteristics corresponds to the changes of the rotational speed of the crankshaft and engine load.

In order to assess the road ecological indicators of the vehicle in the standardized road test SORT 2, the obtained values of road exhaust emission were compared (figure 8). The results presented are the average values of all 16 single drive tests performed. The highest emission value was found for CO₂, which was 1.62 kg/km. This parameter is closely related to fuel consumption and lowering its content

in the exhaust gas is possible by reducing the energy consumption of the drive system and vehicle functional systems. It should be noted that this compound is considered harmful, but it is not defined as toxic. Among the analyzed toxic exhaust components, the highest value of road emissions was observed for CO = 1.57 g/km, then for NO_x = 1.3 g/km and THC = 0.21 g/km. Using the carbon balance method the fuel consumption per 100km was determined. Carbon containing compounds, such as: CO, THC and CO₂ were used for these calculations. The calculations were performed as described in [2, 7]. Road fuel consumption of vehicle in the SORT 2 reached 59.5 dm³/100km. However, it should be kept in mind that in the performed tests the vehicle was loaded with a significant replacement load, which was meant to reflect the standard operation of transporting passengers.

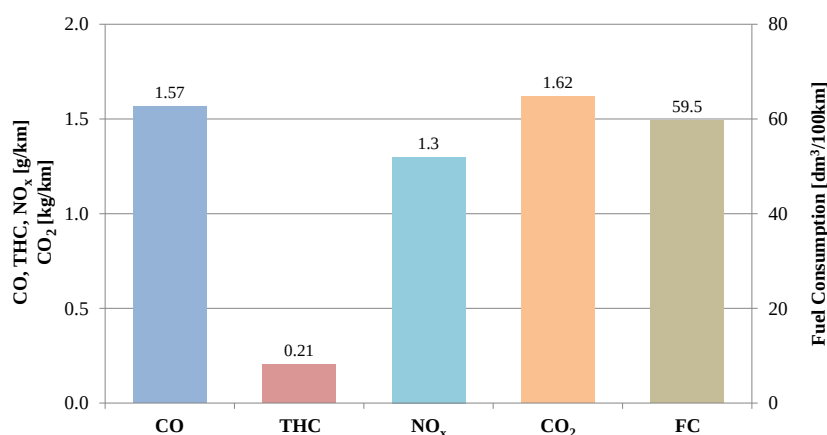


Figure 8. CO, THC, NO_x, and CO₂ road emission and fuel consumption determined from measurement results in the standardized SORT 2 test drive

Due to the specificity of urban bus construction, they are classified as heavy vehicles. Therefore, the legislative guidelines define emission limit values expressed as a quotient of the emitted mass of a given compound to the work performed. The average work performed by the combustion engine of the test vehicle for all drives in the SORT 2 test was 3.91 kWh. The results of the specific emission of the analyzed toxic compounds are presented in figure 9. As for road emissions, the highest values were obtained for CO₂ = 0.74 kg/kWh. For toxic compounds, from the highest to the lowest values these were: CO = 0.7 g/kWh, NO_x = 0.55 g/kWh and THC = 0.08 g/kWh. Comparing the obtained values to the Euro VI standard, it can be concluded that for CO and THC the emission limit values have not been exceeded. On the other hand, for NO_x, the measured values were 20% higher than those defined for the WHTC test. However, it should be noted that SORT driving tests do not meet the RDE conditions, therefore it is impossible to define emission compliance factors for tests in real operation.

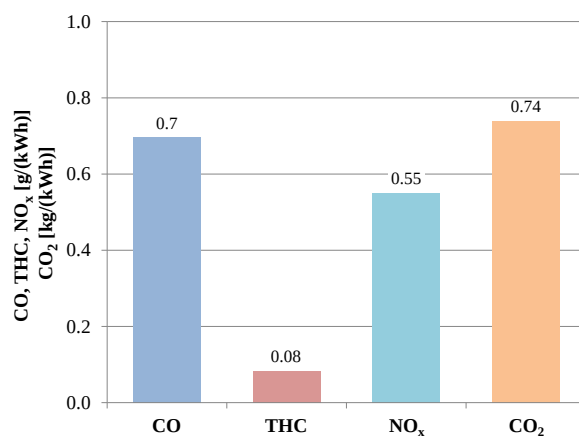


Figure 9. Specific emission of CO, THC, NO_x, and CO₂ determined from measurement results in a standardized SORT 2 test drive

5. Conclusion

As stated in the article introduction, global trends in the development of communication include the limitation of vehicle traffic in urban agglomeration centers. In many areas special norms are introduced for vehicle such as city buses. Due to the advantages and transport possibilities of this group of vehicles, BRT systems are becoming more and more popular. In general, the idea of introducing them is to provide a fast and punctual communication network in which buses are privileged with respect to other road users. Undoubtedly, such systems are attractive for residents of urban agglomerations, however, for environmental reasons it should be ensured that the vehicles used in these systems meet the highest environmental standards – confirmed by tests performed in real operating conditions. City buses exhaust emission measurements in real operating conditions are a relatively new field of study. Therefore, currently developed measurement methods (including vehicle preparation and equipment selection) are constantly being improved.

The article presents exhaust emission results an 18 m long public transport bus. The drive system uses a hybrid solution in a serial configuration. The test object is the basis for developing a vehicle designed specifically for use with BRT systems. The measurements were taken in the SORT 2 drive test, which reflects urban driving conditions. In the adopted methodology, apart from fuel consumption (defined by UITP), measurements of toxic compounds exhaust emission were also performed. The presented research results prove that the performed test drives (16) were made with a high degree of repeatability. The operating conditions of the vehicle and the drive system were assessed using the operating time density characteristics. Both road and specific emission values were taken into account in ecological analyzes. Considering the emission intensity of harmful compounds, the effect of the drive system and exhaust aftertreatment systems on the obtained values was evaluated and the main relations were defined. Among those were the results which showed that: the highest instantaneous emission values occurred during vehicle acceleration, or that for the selected compounds the maximum velocity obtained in the given test section did not have an effect on the obtained fuel consumption values. It was found that only NO_x exceeded the Euro VI limits (by about 20%). It should be noted that SORT driving tests do not meet the established RDE test conditions, therefore the emission compliance coefficients can not be defined. However, the conducted research allows to present an overall picture of the ecological characteristics of the tested vehicle in the defined and selected driving conditions.

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