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Comparison of pollutant emissions per passenger for public and individual transport

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The current policy of the European Union aims to reduce the negative impact of the transport sector on the emission of pollutants generated by combustion engines into the atmosphere. One of the key trends in this expansion is to increase the share of public transport. The article presents a scenario of passenger travel in an urban agglomeration, using a passenger car and a bus. The input data were obtained from tests carried out under real operating conditions using PEMS (Portable Emissions Measurement Systems) equipment. Both objects tested met the same emission standard – Euro 5/V. The obtained pollutant emission values were converted into emissions generated by passengers. The results show that travelling by bus has a much lower impact on the environment, but the journey time is longer and requires the bus schedule to be adjusted to the travel plan.

Key words: *city bus, exhaust emission, passenger car, passenger travel, PEMS*

1. Introduction

The European Union's sustainable development policy is important in the context of protecting the environment, which must be safeguarded for future generations [3]. This issue is significant in the context of civilisational development, which is often associated with the use of natural resources or the degradation of the planet. One of the most serious consequences is the creation of pollution, which intensifies smog, acid rain, and the greenhouse effect, and has a destructive impact on human health [15]. Transport plays an important role here, as it is primarily based on the combustion of fossil fuels – combustion engines and the production of electricity for electric vehicles. The latter source is characterised by different indicators for different regions of Europe and the world [12].

The introduction of emission standards for powertrains, clean transport zones, and other restrictions in the field of transport has a positive impact on environmental protection [1]. Vehicle manufacturers and scientists are constantly working to introduce innovative solutions to improve the ecological parameters of means of transport, including those related to weight, powertrain systems, and travel planning [4, 8, 17]. Current European Union policy and industry activities focus on the use of hydrogen in fuel cells, which is the most promising direction for the automotive industry [5, 9]. However, work is ongoing to assess pollutant emissions as one of the main problems of engine drives [2, 10]. However, it is necessary to continuously educate people about caring for natural resources. In order to ensure good education, it is necessary to provide scientific evidence that will convince people to make efforts to care for the environment, as in the publication [13]. This is the origin of this article, which presents research conducted in real operating conditions on a passenger car equipped with a compression ignition engine and a city bus in order to quantify which means of transport is more environmentally friendly. The results are supplemented by a reference to the pollutant emissions per passenger.

2. Selection of research objects

Based on data from the Central Register of Vehicles and Drivers, at the end of 2023, there were approximately 27 million vehicles in the register, with approximately 7 million being unused vehicles with various histories of termination or long-term interruption of operation [7, 11]. When analysing the average age of passenger cars in Poland, a significant problem can be observed. According to data from the 2022/2023 automotive report, the average age of a passenger car in Poland exceeds 15 years [19]. The exact result is influenced by the determination of the share of the aforementioned unused vehicles. However, the average age indicates that the solutions used in many passenger cars in Poland are outdated, which may also mean increased pollutant emissions. Referring to Central Statistical Office reports, it can be concluded that newer vehicles are used in larger agglomerations. This is particularly evident in the capital, where significant rates of new registrations are achieved. However, it should be remembered that this applies to company vehicles associated with businesses operating or registered in Warsaw.

According to a report by the European Automobile Manufacturers' Association (ACEA) [21], the average age of buses operating in our country is 16 years. For city buses, the rates are highly varied depending on the area of use. In large agglomerations, younger fleets are used. This is due to ongoing investments, a high level of subsidies, and European Union requirements in this regard. On the other hand, older fleets are used on suburban lines and in small towns, often several decades old, with millions of kilometres on the clock.

Based on the data presented on vehicle age and the objective of the article, two research objects were selected. The first was a passenger car with a conventional drive system using a compression ignition engine, referred to in the article as a passenger car (Fig. 1). The manufacturer's declaration ensures compliance with the Euro 5 standard. In terms of internal and external exhaust gas treatment systems, the following were used: EGR (Exhaust Gas Recirculation), DOC (Diesel Oxidation Catalyst), and DPF (Diesel Particulate Filter). Table 1 presents the basic data on the research object. The maximum torque of 250 Nm is achieved in the range from 1500 to 2500 rpm, thanks to the use of turbocharging. The maximum engine power is 81 kW at 4200 rpm.

Fig. 1. View of the tested passenger car with measuring equipment

Table 1. Characteristics of the research object – passenger car

Parameter	Unit	Value
Year of manufacture	–	2011
Vehicle weight	kg	1266
Layout, number of cylinders, valves	–	In-line, 4, 16
Displacement	dm^3	1.968
Power at rotational speed	kW at rpm	81 at 4200
Torque at rotational speed	Nm at rpm	250 at 1500–2500
Compression ratio	–	16.5:1
Turbocharging	–	turbocharger
Exhaust gas treatment systems	–	EGR, DOC, DPF
Exhaust emission standard	–	Euro 5

The second research object was an 18-metre-long city bus, also with a conventional internal compression ignition engine, referred to in the article as a city bus (Fig. 2). It complied with the EURO V – EEV standard. Table 2 presents the characteristic data of the research object. The maximum torque produced by the engine occurs at a crankshaft speed of 1100 rpm, which indicates its adaptation to urban traffic conditions, where frequent stops and starts are common – particularly important in the case of city buses.

Fig. 2. View of the tested city bus

Table 2. Characteristics of the research object – city bus

Parameter	Unit	Value
Year of manufacture	–	2009
Vehicle weight	kg	16 000
Layout, number of cylinders, valves	–	In-line, 6, 24
Displacement	dm^3	9.186
Power at rotational speed	kW at rpm	228 at 2200
Torque at rotational speed	Nm at rpm	1275 at 1100–1700
Compression ratio	–	17.4:1
Turbocharging	–	turbocharger
Exhaust gas treatment systems	–	EGR, DOC, DPF
Exhaust emission standard	–	EURO V

3. Research methodology

3.1. Measurement equipment

Portable Emissions Measurement Systems (PEMS) were used to test the vehicles, measuring toxic compound concentrations under real operating conditions [6, 16]. The environmental assessment of the passenger car was carried out using the Axion R/S+ device. This analyser enables the measurement of both gaseous compounds and particulate matter concentrations. Non-dispersive infrared analysers were used to measure the concentrations of carbon monoxide, carbon dioxide, and hydrocarbons, which determine the absorbed radiation in a narrow wavelength band characteristic of a given substance. The result obtained is compared with the radiation absorbed by the reference gas [14]. For nitrogen oxides and oxygen concentrations, an electrochemical method is used, based on the conversion of an electrical signal. The exhaust gas flow is calculated using parameters read by the OBD system or information from sensors (rotational speed, temperature, and pressure in the intake system) [20].

The city bus was tested using a Semtech DS device. The device measures hydrocarbon concentrations using a FID (Flame Ionisation Detector) analyser, while carbon monoxide and carbon dioxide concentrations are determined using a non-dispersive infrared analyser, as in the Axion R/S+. The concentration of nitrogen oxides is determined in a non-dispersive analyser using ultraviolet light. A mass exhaust gas flow meter is required to determine the concentrations of harmful compounds [20].

Both instruments were calibrated and prepared for operation in accordance with their instructions before measurements were taken [20, 21]. GPS positioning systems were also used in the study to obtain data on vehicle movement parameters. All calibrated measuring elements acquired data at a frequency of 1 Hz.

Due to the specific nature of real-world operating conditions, especially in urban areas, it is impossible to obtain identical journeys on a given route. The paper presents the results of individual journeys in which uninterrupted, continuous measurements of pollutant emissions and vehicle operating parameters were performed. This is an advantage of road tests over tests in repeatable conditions (e.g. chassis dynamometer, engine dynamometer), as it allows the impact of various factors on the results obtained during road tests to be assessed. In accordance with the accepted and applied standards, the measuring instruments used can be successfully used in tests during actual operation, as they have the appropriate certificates (including EU 2016/427 compliance). Their data are presented in Table 3.

Table 3. Technical specifications of the portable exhaust emission analyzers: Axion R/S+ and Semtech DS [18, 20]

Axion R/S+		
Parameter	Measurement method	Accuracy
Component concentration:		
CO	NDIR, 0–10%	±3%
HC	NDIR, 0–4 000 ppm	±3%
NO	electrochemical, 0–5000 ppm	±3%
CO_2	NDIR, 0–20%	±3%
O_2	electrochemical, 0–25%	±1%
Semtech DS		
Parameter	Measurement method	Accuracy
Component concentration:		
CO	NDIR, 0–10%	±3%
HC	FID, 0–10 000 ppm	±2.5%
NO_x	NDUV, 0–3000 ppm	±3%
CO_2	NDIR, 0–21%	±3%
O_2	electrochemical, 0–21%	±1%
Exhaust gas flow	mass flow rate T_{max} to 700°C	±2.5% ±1%

3.2. Research route

Research on pollutant emissions from research objects was conducted under real operating conditions in the Poznań agglomeration. The research route covered a transport line operated by a local transport company. It ran through the city centre, with the end points being the Dębina and Sobieskiego housing estates in Poznań (Fig. 3). This choice of test route made it possible to compare the results obtained for a passenger car with the emission tests for a city bus. The measurements were carried out on a weekday, around midday. The total length of the test route was 17.2 km. It consisted of sections with varying speed limits (from 30 km/h to 50 km/h).

Fig. 3. Research route [19]

4. Analysis of operating conditions of research objects

The bus under test was operating according to the scheduled service on a route operated by the local transport company. To achieve the objective of the study, the passenger car was operated on the same route, but without stopping at bus stops. The characteristics of the speeds achieved by the research objects are presented in Fig. 4. In both measurement cycles, the vehicles achieved similar maximum instantaneous speeds (approximately 50 km/h), which was due to the characteristics of the traffic arteries and the restrictions applied in the agglomeration. The average speeds were 22.6 km/h for passenger car and 15.7 km/h for bus. The city bus achieved a lower average result, which was due to the need to serve passenger stops.

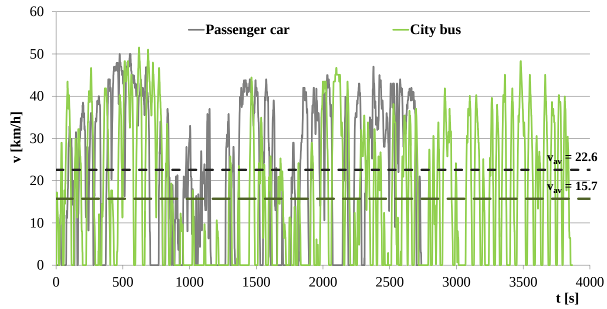

Fig. 4. Velocity characteristics of the research objects

The data collected during measurements in urban traffic conditions concerning vehicle speeds throughout the test and corresponding accelerations are presented as a function of time density. Figure 5 shows the characteristics of vehicle operation during test runs.

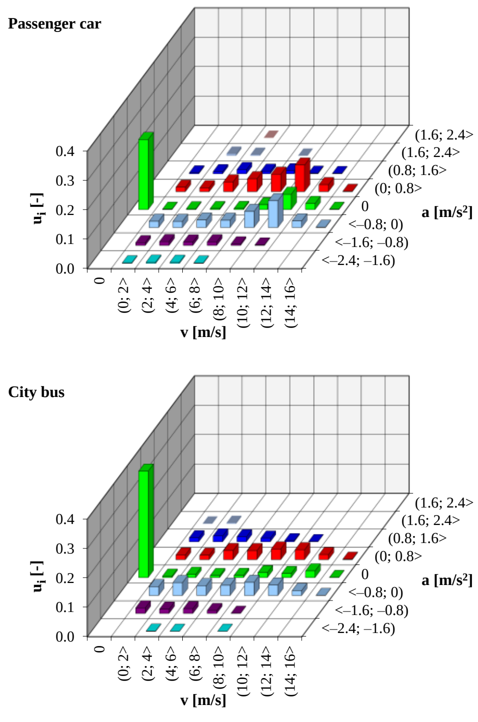

Fig. 5. Shares of vehicles operating time in speed and acceleration compartments during road tests

In both tests, the largest share of operating time was recorded for stops, respectively: 24% for passenger cars and 36% for city buses. The data presented shows that neither vehicle moved for almost a quarter of the test journey, which was due to the traffic conditions in the city centre. The greater share of operating time spent by city buses at stops was due to serving bus stops. The values for the extreme intervals are the lowest, which indicates that sudden braking or acceleration occurred very rarely. For both vehicles, accelerations above 0.8 m/s^2 accounted for up to 7% of the test time, and decelerations below –0.8 m/s^2 accounted for up to 6% of the test time. In total, therefore, acceleration values exceeded the ±0.8 m/s^2 range for approximately 13% of the test time. Referring to the traffic results at a constant speed, where a = 0 m/s^2, 10% and 8% of the test time were obtained for the objects, respectively. Apart from the aforementioned ranges at zero acceleration, the passages were dominated by conditions in the range of accelerations from –0.8 m/s^2 to 0.8 m/s^2.

5. Comparison of environmental indicators for vehicles

Based on the data recorded by the analysers and auxiliary devices, the road emissions of the research objects during the tests were determined (Fig.6). Based on the results obtained, it can be concluded that the city bus achieved approximately three times higher CO_2 road emissions (1230 g/km). This harmful compound is directly dependent on fuel consumption, which was undoubtedly influenced by the weight of the tested objects.

Road emissions of CO and HC were several times higher for the passenger car, which achieved 9.84 g/km (approximately 4 times more than the bus) and 1.88 g/km (approximately 3 times more than the bus), respectively. The design of the drive systems had a significant impact on these differences in results. The combustion engine of a city bus, together with the gearbox, is designed for the characteristic operating conditions on city routes – frequent stops and accelerations. The crankshaft speed range is limited, and the rated torque parameters are already present from 1100 rpm. A passenger car's drive system must be more versatile, i.e. it is designed for use not only in urban conditions, but also in non-urban conditions and on motorways. The combustion engine used operates in a much wider range of crankshaft speeds. During the tests, the passenger car did not simulate stop operations. Frequent stops related to urban infrastructure had a direct impact on the occurrence of unstable operating conditions of the combustion engine. This confirms that the road emission results obtained indicate a significant contribution of incomplete and partial combustion to the processes occurring inside the combustion engine.

NO_x emissions in internal combustion processes are directly related to engine load and thus to the temperatures occurring at the flame front. For a passenger car, the specified value of the aforementioned relationship reached 1.08 g/km. This was approximately 10 times lower than for a bus (9.87 g/km). It should be noted that in a passenger car, the EGR system was primarily responsible for limiting NO_x emissions. In contrast, in the city bus, in addition to EGR, an SCR (Selective Catalytic Reduction) system was used. However, it should be noted that its operation is not continuous and depends on the parameters of the exhaust gas flow (temperature, mass flow).

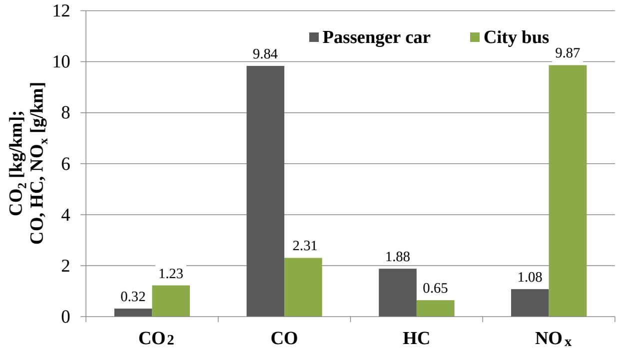

Fig. 6. Road emission of toxic compounds for research objects

The relationship between road emissions and the number of passengers is shown in Fig. 7. For a passenger car, the maximum number of passengers could be 5. However, during testing under real operating conditions, there were 2 people in the vehicle: the driver and the equipment operator. The entire set of apparatus, including electrical energy storage devices, weighs approximately 60 kg. The pollutant emission results obtained were divided by 3, thus taking into account the weight of the measuring equipment. In the case of a city bus, the vehicle configuration allowed for 40 seats and 135 standing places. The bus load was assumed to be 50% of capacity due to the high passenger traffic on this route, so the road emission value obtained was divided by 88. This value was adopted based on passenger exchange on the bus during testing, and the guidelines contained in EU Regulation 582/2011 were also taken into account.

Based on the determined relationships, it was concluded that public transport is significantly more environmentally friendly than individual transport, such as the passenger car analysed. The CO_2 emissions balance would be equal between the two vehicles if 10 people travelled on the bus. For NO_x, similar values would be achieved when transporting 25 people in a city bus. City buses are public transport vehicles used for the mass transport of people over short distances in urban traffic conditions. Passenger cars have far fewer seats and are not designed exclusively for use in urban traffic.

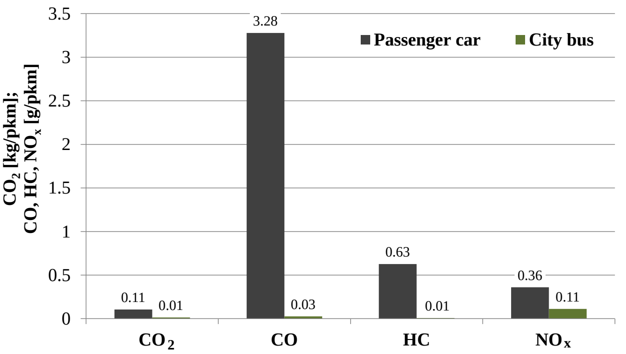

Fig. 7. Summary of road emissions per passenger during tests

6. Emissions from vehicles in urban areas

Passenger cars remain an important element of the transport system in urban areas, accounting for a significant proportion of daily passenger transport. Considering the key role of passenger cars in cities and their average age in Poland, it can be assumed that a significant percentage of vehicles in use are less technically efficient, which may result in higher levels of pollutant emissions. In addition, the long-term use of conventionally powered passenger cars exclusively for short journeys (e.g. commuting to work, service premises, etc.) is disadvantageous both in terms of pollutant emissions and vehicle operation. Such use hinders the effective operation of exhaust gas treatment systems and may also result in increased fuel and engine oil consumption, as well as accelerated mechanical wear of engine components.

The emission results for passenger cars and city buses per passenger clearly show that public transport is more advantageous. This is due to the significantly greater capacity of such vehicles. Another important aspect is that, regardless of the traveller's choice of transport, public transport vehicles will continue to run their routes because they operate according to a pre-determined timetable. In this respect, when analysing pollutant emissions, it was found that pollutant emissions from city buses will occur anyway (in amounts depending on the number of passengers), while pollutant emissions from passenger cars are an additional burden on the environment. For this reason, public transport should be used, as increasing the number of passengers also reduces the rate of harmful emissions per passenger.

However, it is not always possible to use public transport exclusively. In this case, it is environmentally beneficial to travel by car with a larger number of passengers. Therefore, in order to reduce harmful emissions into the atmosphere, solutions such as carpooling should be promoted. This is a form of travel that involves sharing a car journey with several people (at least two) travelling on the same or a similar route. This is not a form of commercial activity – the driver does not make a profit from the journey, but only receives compensation for the costs incurred. Thanks to this solution, it is possible to use the space in vehicles more efficiently, reduce the number of vehicles on the road, and limit the amount of pollution per passenger.

7. Summary

The research conducted revealed differences in the operational characteristics of passenger cars and city buses. Despite similar maximum speeds achieved in urban traffic, the average speed of a passenger car was higher (22.6 km/h) than that of a bus (15.7 km/h), which was due to the need for public transport vehicles to serve stops. An analysis of the distribution of accelerations and decelerations showed that both vehicles were stationary for a significant part of the time (24% for cars and 36% for buses), which is characteristic of congested urban infrastructure.

The research revealed significant differences between the vehicles analysed. Due to its greater weight and fuel consumption, the city bus generated approximately three times more CO_2 emissions (1230 g/km) than the passenger car (320 g/km), but had significantly lower CO and HC emissions thanks to the adaptation of the drive system to urban conditions. On the other hand, NO_x emissions were significantly higher for buses (9.87 g/km) than for passenger cars (1.08 g/km), which was due to different exhaust gas reduction systems and drive unit loads. However, when emissions were related to the number of passengers, public transport clearly had the advantage – even when the public transport vehicle was only partially full, the unit emissions per passenger were significantly lower. This means that, from an environmental perspective, the development and promotion of public transport is a key element in reducing emissions in urban areas.

Passenger cars, despite their important role in everyday urban transport, generate a significant environmental burden, especially due to their high average age and unfavourable operating conditions on short journeys. Inefficient exhaust gas treatment systems and intensive mechanical wear increase pollutant emissions, which, when calculated per passenger, make individual transport less efficient than public transport. City buses, which operate on fixed routes regardless of the number of passengers, have a more favourable emissions balance per person. Therefore, in order to reduce the negative impact of transport, it is necessary to promote alternative solutions, such as public transport or carpooling, which, through more efficient use of vehicles, can reduce the number of cars on the roads and the level of emissions in cities.

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Nomenclature

a	acceleration
CI	compression ignition
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
EGR	exhaust gas recirculation
PEMS	portable emissions measurement systems
SCR	selective catalytic reduction
t	time
u_i	share of working time
v	velocity

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