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Energy Consumption and Driving Parameter Analysis in an 18-Meter Long Urban Bus with Compression Ignition Engine

Łukasz Grabowski[1]

[1] Faculty of Mechanical Engineering, Lublin University of Technology, Nadbystrzycka 36, 20-618 Lublin, Poland
E-mail: l.grabowski@pollub.pl

ABSTRACT

Urban buses equipped with compression ignition engines are still in use and currently account for more than 70% of all urban buses in use worldwide. This article discusses the results of the one-year research on the energy consumption by urban buses in Poland. The research object was a Mercedes Conecto. The analyses were carried out on an annual and monthly. The energy consumption was evaluated from the calculations of 284 days of operation. The average vehicle speed and average energy consumption were calculated as 16.05 km/h and 19.78 MJ/km, respectively. The distributions of energy consumption and average speed are plotted on the histograms. The next step was to determine the dependence of energy consumption on the daily distance covered, ambient temperature, and average speed. It was shown that an increase in average speed by 1 km/h results in a reduction of 0.65 MJ/km in fuel energy consumption, and an increase in ambient temperature results in a reduction of 0.06 MJ/km. In addition, the study shows a daily distance range from 210 to 220 km with the highest specific energy consumption of more than 21 MJ/km. The research results can be useful for improving the energy efficiency of public transport modes.

Keywords: energy consumption, fuel consumption, city bus, diesel engine.

INTRODUCTION

Public transport is an important part of the sustainability of modern cities. City buses are a popular and efficient means of transport used in many cities around the world. The advantages of public transport are low energy consumption and emissions per passenger. In addition, buses run on more flexible though fixed routes than trains, which is important when bus routes are to be adapted to a growing city. At the same time, city buses have lower implementation and operating costs than trams or metros.

Actually, the means of urban transportation include trams, buses and metros. The choice of type of public transportation is influenced by factors such as the development of road infrastructure, adopted development policies, preferences of city inhabitants, and the financial feasibility of implementing new means of transport. Recent years have seen the development of urban transport and the popularization of low-emission vehicles. Low-emission vehicles include electric and hybrid buses. However, the share of compression ignition engines powered city buses in operation remains significant.

At preset, the number of buses is increasing [1], which is in response to the growing environmental awareness of city inhabitants and the ongoing need to improve urban air quality. Bus vehicles equipped with modern engines and powertrains are great contributors, which is linked to the introduction of sustainable transport solutions. The results in the publication [2] on the urban transport in Jakarta serve as a good example. In this case, buses are presented as the main public transport system and serve approximately 140 bus routes. The analyses conducted between January 2016 and February 2020 showed that the bus route network significantly grew so the exported buses more than doubled from 700 to more than 1.600 units. The analysis of the fleets of city buses currently in operation around the world clearly shows that most of them is equipped with compression ignition engines. This is due to high investment costs in new hybrid or electric bus technologies that are definitely more expensive than buses with compression ignition engines. The data in the paper [3] shows that in December 2022 about 77% of all buses with close public transport were equipped with compression ignition engines, and 50% of this group were vehicles powered by engines equipped with an advanced exhaust gas component control system. This means that the energy consumption of urban transport vehicles with compression-ignition engines is still relevant and should be studied, especially in terms of specific locations.

STATE OF THE ART

Energy consumption in the transportation sector is constantly increasing due to the growth of civilization and technologies over the last few decades (1972 1012) [4, 5]. Total energy consumption in transport has increased from 40.3 EJ to more than 105 EJ, and the largest increase has been recorded in countries beyond the Organization for Economic Cooperation and Development. Among energy sources, fuels derived from oil continue to dominate. There is some increase in the share of biofuels and natural gas. The paper [6] shows the difference in energy efficiency of different modes of transport, with the emphasis that public transport is the most efficient.

The literature describes many factors [7, 8] behind the fuel consumption of a city bus. One of the fundamental factors is traffic volume due to the number of vehicles. Traffic volume significantly affects average speed of the vehicle. The factors that determine the energy efficiency of urban buses are described in [9]. Several of them are discussed, but average vehicle speed, road gradients above 5 % and the characteristics of the bus routes are given as key factors. Of lesser importance is here the occurrence of traffic incidents such as engine braking or too high engine speed kept by drivers.

The results in [10] showed a key impact of weather conditions. They can considerably increase fuel consumption. In the case studied, the temperature varied from - 35 to 35 °C. The results obtained confirm the largest increase in fuel consumption when road conditions deteriorated due to low temperatures. It was found that this fact can increase fuel consumption between 18 and 74% compared to the established norm.

Factors such as different speeds, acceleration and deceleration modes, and dwell time at bus stops are crucial in determining fuel consumption in urban transport. Other important variables affecting the energy efficiency of urban buses include vehicle types, average speed, and the slope of roads. In general, energy consumption in transport depends on factors such as the type of vehicle (maximum weight, type of drive unit), traffic conditions (traffic jams), and climate (temperature changes).

The literature discusses various results of transport energy efficiency [11, 12]. One of these is, for example, the research on how driving strategies influence fuel consumption, and the main focus was put on the uniqueness and unpredictability of drivers' behavior. The results indicated that even a small percentage of the replacement of classic vehicles by autonomous vehicles would have a positive impact on the overall energy efficiency of transport. This finding is fundamental for vehicles used in urban traffic conditions.

The ecological efficiency of means of transport is also assessed. Such a case could be the results obtained in Brazil [14]. This study considered eleven different transportation methods and four variables: load capacity, fuel efficiency, total emissions, and energy consumption. The results showed that the use of DEA (Data Envelopment Analysis) enabled a thorough operational analysis and a better differentiation of transport modes in terms of the ecological efficiency of the analyzed vehicles.

Many different factors must be considered if energy consumption in transport modes is researched. For example, the work [15] analyzed the historical data on energy consumption in road transport in Europe. The analysis referred to the impacts of the country's economic growth, demographics, fuel prices, passenger numbers, tonne-kilometers, and the individual characteristics of vehicle fleets. These parameters were available in the 1995–2018 findings. The results of this analysis include an assessment of the energy efficiency and achieved reduction of CO_2 emissions referred to the European Union's 2030 and 2050 targets. The authors showed that the introduction of energy efficiency and decarbonization policies resulted in a stabilization of vehicle energy consumption despite the number of vehicles increased. This finding shows that low-emission propulsion systems, including compression ignition engines, should be developed, fleet management should be correct and efficient, and means of transport should be correctly selected.

One of the fundamental factors behind energy consumption in the transport sector is the growing number of vehicles, which, due to traffic jams, simultaneously interrupts vehicle traffic flow. The results of the model tests presented in [16] showed that by 2050, compared to 2013, total emissions and fuel consumption will increase 65 and 62 times, respectively. It is obvious that restricting private vehicles and implementing an integrated public transport system can cut emissions and fuel consumption by 34%.

It should be emphasized that all the results refer to the selected cities and locations but there no results for cities in Poland with average annual temperatures above zero and a temperate climate. Research on factors influencing energy efficiency for a given city are for example in [16, 17]. Therefore, it was decided to study the energy consumption of a city bus operating in a city in Poland to gain the data that will contribute to better energy efficiency of transport modes. In this case, the key issue to be solved is to describe quantitatively the dependence of energy consumption on operating conditions such as average vehicle speed and ambient temperature. Such results will make it possible to adapt the modes of operation of means of transport to specific weather and road conditions and better understand the factors behinds energy efficiency for a given city [18].

Having in mind the above aspects, the study aims at specifying the impact of average driving speed and ambient temperature on the energy consumption of a city bus with a compression ignition engine. The tests were carried out over one year of vehicle operation in the city of Lublin. Located in eastern Poland, Lublin is the eighth-largest Polish city with a population of approximately 340.000 inhabitants. This city covers an area of 148 km^2. The analyses were based on daily measurements performed at a frequency of 2 Hz.

SCOPE OF THE RESEARCH

The research was carried out in Lublin. Lublin, one of the largest cities in Poland, has an adapted public transport system. It consists of trolleybus lines (15 lines) and bus lines (62 lines). The lines are served by over 400 vehicles.

The research was carried out for a period of one year due to the assumed aims. Over this time, the tested bus was used for 284 days. The remaining days included maintenance checks or days when the bus was not scheduled for use, such as weekends or holidays.

The object of the research was a Mercedes Conecto bus (Fig. 1) used by the Municipal

Figure 1. Mercedes Conecto 18 bus [Wendeker et al. Measurements and analysis of a solar-assisted city bus with a diesel engine. Applied Energy, 2022, 309, 118439]

Transport Company in Lublin. This bus is an 18-meter, low-floor model with a maximum capacity of approximately 150 passengers and a maximum permissible weight of 28.000 kg. It is equipped with a Mercedes-Benz OM 457 HLA compression ignition engine with an effective power capacity of 220 kW. The engine has an automatic transmission. The drive unit is mounted in the left rear corner of the vehicle. The vehicle meets the Euro V exhaust emission standard.

The recorded parameters include: vehicle speed, volumetric fuel consumption *G*, crankshaft speed ne, daily distance D_d and ambient temperature *t* (Table 1). All data were recorded at a frequency of 2 Hz from 4:00 a.m. to 12:00 p.m. The recorded results were saved on a memory card placed in the measurement system in the vehicle. The results were recorded using the GSM network once a week on the data server.

DATA ACQUISITION SYSTEM

A mobile real-time registration system using a GPS sensor and diagnostic system transmission (Figure 2) was developed and installed on the bus.

Table 1. Research scope

Defined parameter of scope	Value
Measurement time	1 year
Real measurements days	284
Daily measurement hours	4:00–23:30 (19 hours)
Recording frequency	2Hz
Recorded parameters	Volumetric fuel consumption, vehicle speed, engine speed, ambient temperature, odometer

The applied real-time data recording system was based on Compact RiO ncRIO 9024 by National Instruments and equipped with some measurement cards: CAN interface NI 9862 and RS485/RS422 NI 9871 (Figure 3).

The following data was obtained from the bus diagnostic transmission (PROFIBUS transmission protocol): vehicle speed V, distance D_D, operating time t, external temperature *t*, crankshaft speed ne, hourly fuel consumption G. The data was read out by a special interface software. This solution enabled the data contained in the FMS standard transmission to be converted into data writable in a file in accordance with the TDM data model (LabVIEW Binary Measurement File). Consequently, the required disk space for archiving measurement results was reduced. All results were recorded every day at a frequency of 2 Hz, from 4:00 a.m. to 11:30 p.m. Such a start and end time of the measurement was selected to always record the required data when bus was operating.

The results were archived once a week on a server located at the Lublin University of Technology. The measurement system installed on the vehicle is shown in Figure 2, while the diagram of the measurement system in Figure 3.

The results were analyzed using the NI Diadem software. In order to automate the data analysis, computational scripts were written with Visual Basic. Such an approach made it possible to perform calculations from all files without separate calculations in every single file. This involved loading files with the data from the entire month into the computer's memory, and then performing calculations and saving the obtained results. Figure 4 shows the software.

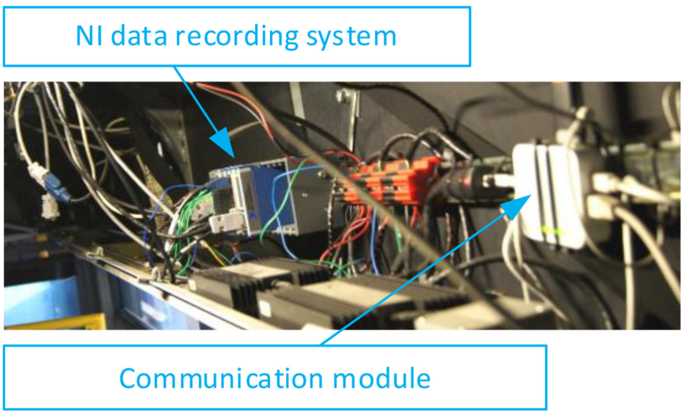

Figure 2. Data recording system installed on the bus

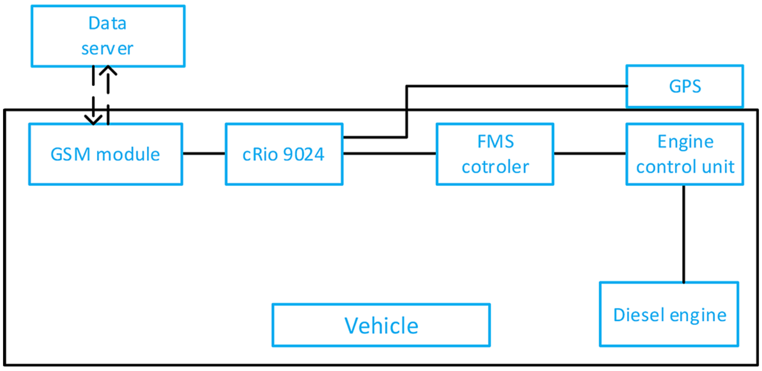

Figure 3. Scheme of the data acquisition system

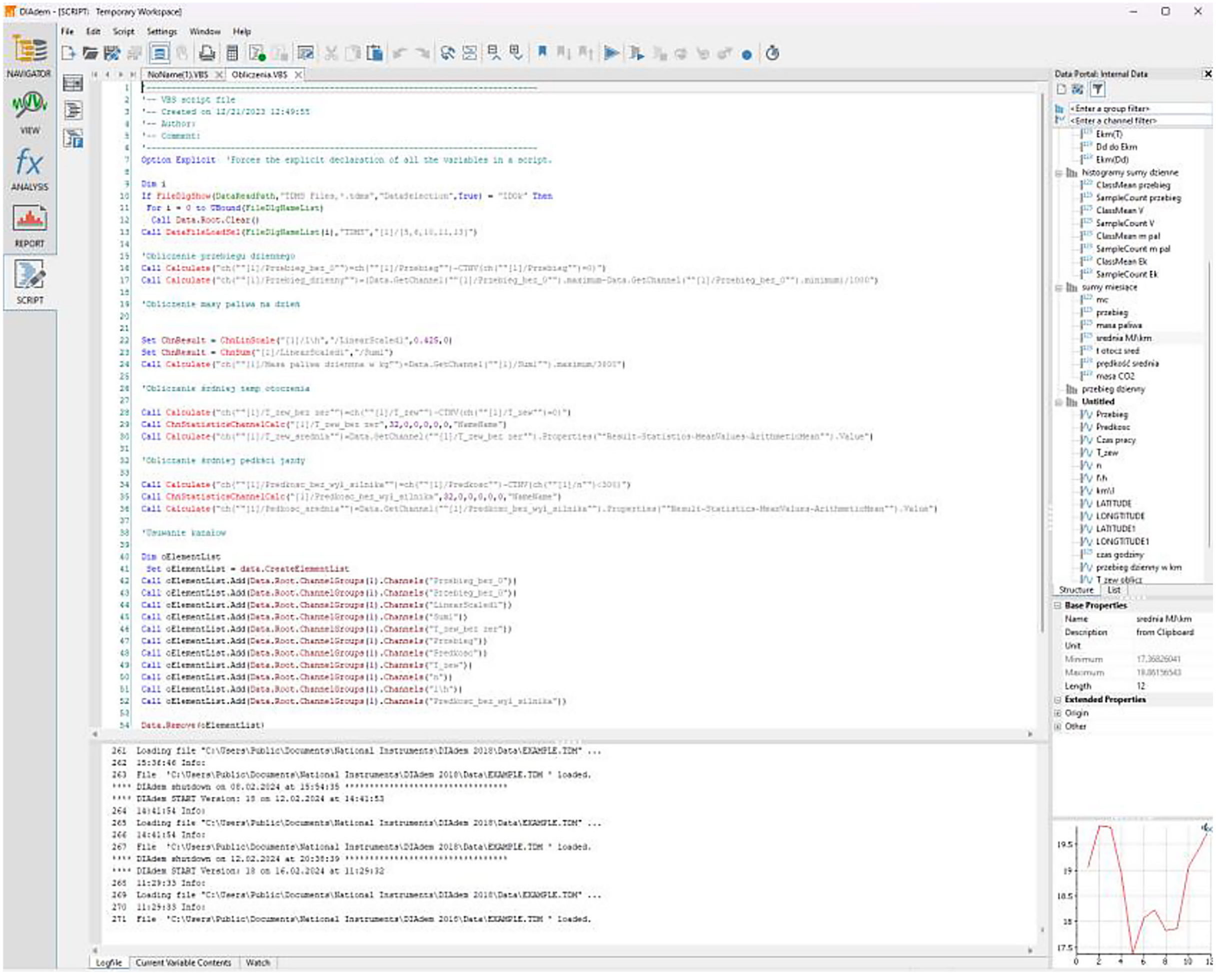

Figure 4. NI Diadem software

RESULTS

Figure 5 shows the measurement results from a single sample day. These are the time courses recorded from 4:00 a.m. to 8:30 p.m. and cover 19.5 hours of measurements. The total working time of bus drivers is less and amounts to approximately 18.5 hours. The first three show vehicle speed V, fuel volume consumption G, and engine crankshaft rotational speed n_s. The gaps between successive values (zero values) correspond to stops at the end stops. The vehicle speed V reaches maximum values in the range of 40 to 55 km/h. The volumetric fuel consumption G varies from zero to 60 dm^3/h. It is characteristic that the value of the maximum fuel consumption value G changed significantly in the second section of the figure. This may mean a change in

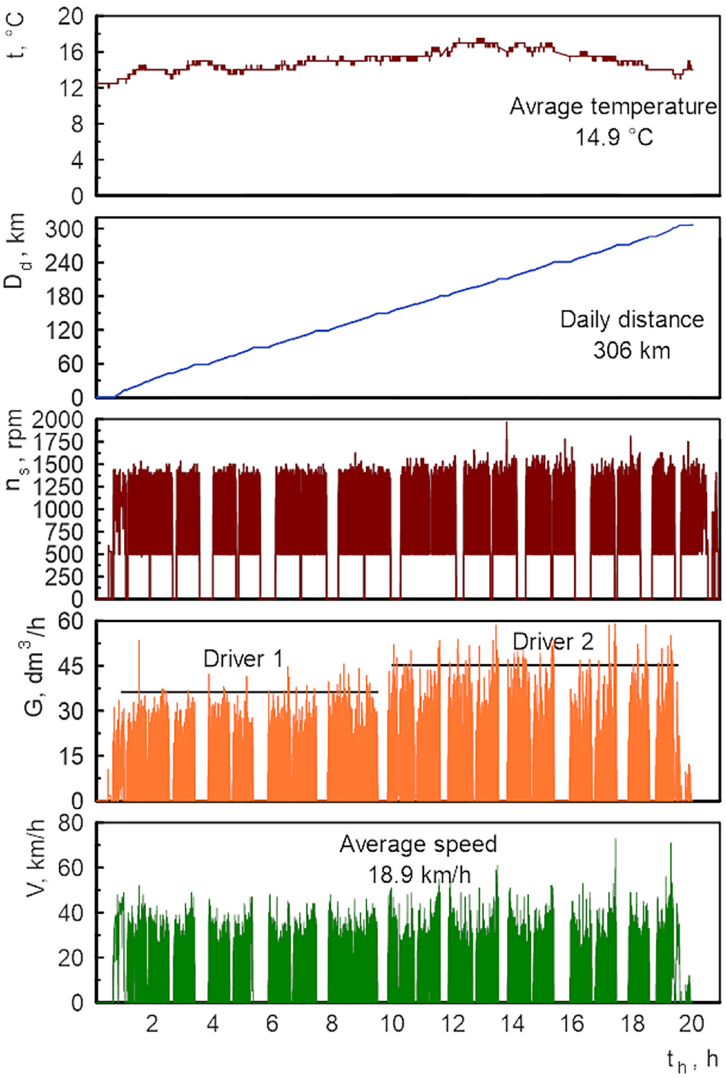

Figure 5. Sample single-day measurement results (bottom-up): vehicle speed, fuel consumption, engine speed, daily distance, ambient temperature, a sample day of June 15

the driving style of the next driver who started his shift after about nine hours. This fact is also clear in the time course of the crankshaft rotational speed of engine n. In this case, an increase in the maximum values of the crankshaft rotational speed of engine can also be seen from 10:00 a.m. It follows that there was a significant increase in fuel consumption per 100 km, because the vehicle speeds V are the same as those of the first driver because they result from specific road conditions.

The next two figures plot the daily distance D_D of approximately 300 km and the changes in the ambient temperature *t* from 4:00 a.m. to 12:00 p.m. The changes in the temperature *t* are negligible, i.e. from 12 °C to approximately 16 °C due to the fact that the sample results were recorded in June.

Figure 6 shows the measurement results registered with the GPS sensor. The recorded values of longitude and latitude were plotted on the map of Lublin. This is one of the sample measurement days, i.e. August 6. The black route is the morning bus route from the depot to the starting stop. Marked in pink, the daily bus route was 12 km long and traveled 16 times per day. Reaching the starting stop in the morning and returning to the depot in the evening is a distance of approximately 15 km.

DISCUSSION

Annual analysis

The first stage to analyze the measurement results was to perform calculations for each measurement day with the NI Diadem software which followed the prepared calculation scripts

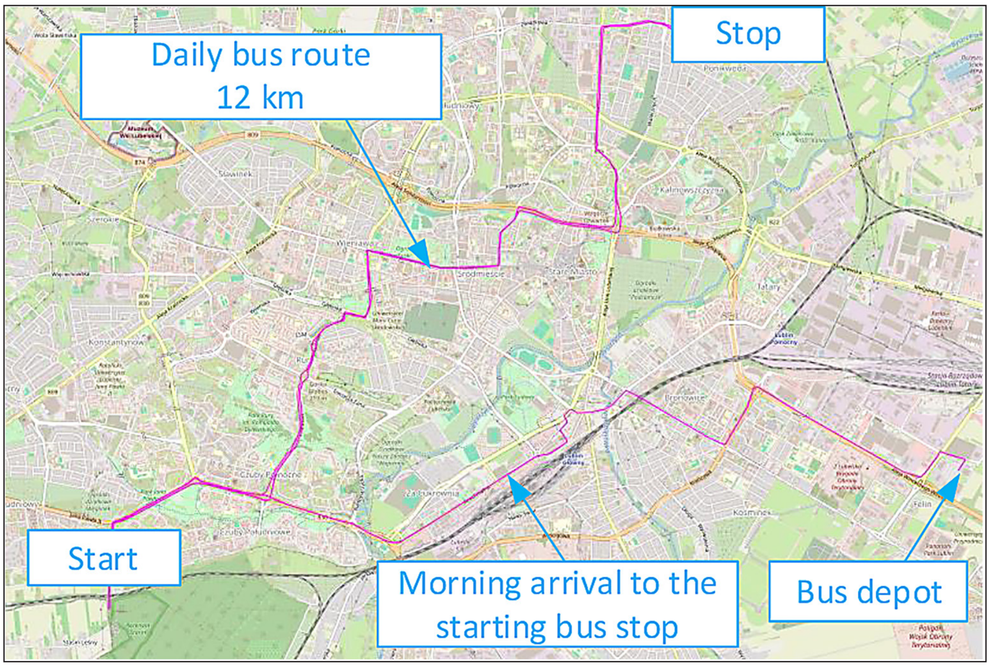

Figure 6. Bus driving cycle in a sample day (August 6) in Lublin, Poland

that automated the calculation process. The results, especially the course of the volumetric fuel consumption G obtained from the FMS standard system, the instantaneous power in the P_f fuel was calculated and then the E_{km} fuel energy necessary to drive 1 km. The procedure is described in detail below.

The instantaneous energy and power in the P_f fuel consumed by the engine was calculated from formula 1 that includes the recorded volumetric fuel G consumption, fuel density ρ = 0.82 kg/dm [3] and calorific value W_o = 43 MJ/kg.

$$P_f = G \cdot \rho \cdot W_o \tag{1}$$

The total energy consumption E_{km} per kilometer of the road consumed in a single day was calculated from the calculated fuel power. The E_{km} value expressed in MJ/km was calculated as the definite integral of the product of the fuel power divided by the number of kilometers run in a given day. The vehicle operating time was assumed as the integration limits t_{s1} and t_{s2}, and the integration step dt was equal to 0.5 s.

$$E_{km} = \frac{\frac{1}{3600}\int_{t_1}^{t_2} P_f(t)\cdot dt_s}{D_d} \tag{2}$$

Additionally, the energy consumed per kilometer of driving was calculated from the results that were recorded only when the following condition of the rotational speed of the engine crankshaft was met:

$$n_e > 0 \tag{3}$$

It follows that this condition neglects the time when the bus was at the final stops with the turned off engine.

The daily distance D_D was calculated as the difference between the recorded total vehicle distance at the end of the day, D_{D2}, and the odometer readings recorded at the beginning of the measurement in a given day, D_{D1}.

$$D_D = D_{D2} - D_{D1} \tag{4}$$

The fuel mass consumed per day, m_f, was calculated as the definite integral of the product of the volumetric fuel consumption G and fuel density r = 0.82 kg/dm^3.

$$m_f = \frac{1}{3600}\int_{t_1}^{t_2} G(t)\cdot \rho \cdot dt_s \tag{5}$$

The carbon dioxide emissions in kilograms were calculated as the product of the fuel mass m_f and the carbon dioxide emission factor for diesel fuel f_{co2} which is 3.19 kilograms of CO_2 per kilogram of diesel fuel used [19].

$$m_{CO_2} = m_f \cdot f_{CO_2} \tag{6}$$

The selected parameters such as daily distance D_D, fuel consumption m_f expressed in kilometers, energy consumption per kilometer and emissions marked as X in formula 7 were summed up for each month.

$$X_n = \sum_{k=0}^{n} x \tag{7}$$

Figure 7a shows the plotting the results summed up or averaged for subsequent months. The following observations can be made in the case of the traffic conditions determined by the total monthly distance and average vehicle speed. The monthly distance traveled by the vehicle ranged from approximately 3,500 km to approximately 7,000 km. This distance reflects two aspects, i.e. a current demand for the vehicle and vehicle efficiency. The monthly distance results from the plans the vehicle is to be used so it was completely determined by the urban transport plans.

A different approach is taken to the average speed that results from many factors. It is clear that the average speed (Figure 7b) recorded in the following months remains similar over the entire year. Its average value is approximately 15 km/h but there are slight seasonal differences. The higher values were recorded in the summer months, whereas the lowest in the winter ones. This fact comes from road conditions in the Central and Eastern Europe climate zone. This can be associated with the average temperature in a given month, see figure 8c. The temperature varied from about 4 °C to nearly 25 °C. The lower temperatures indicated more severe traffic conditions due to snowfall and icy roads.

The total mass of fuel used in individual months plotted in Figure 7e resulted from the distance the vehicle traveled in a given month and is closely correlated with it. The coefficient of the mass of fuel consumed versus the vehicle distance, R2, is linear and equal to 0.95. In this case, the research cannot clearly explain whether the season or month when the vehicle is operated affects the mass of fuel consumed, but obviously the fuel mass is the result of the kilometers traveled in a given month.

The mass of carbon dioxide emitted is directly proportional to the mass of fuel used. The research bus emitted approximately 4.700 kilograms of carbon dioxide in April and approximately 9.500 kg in September.

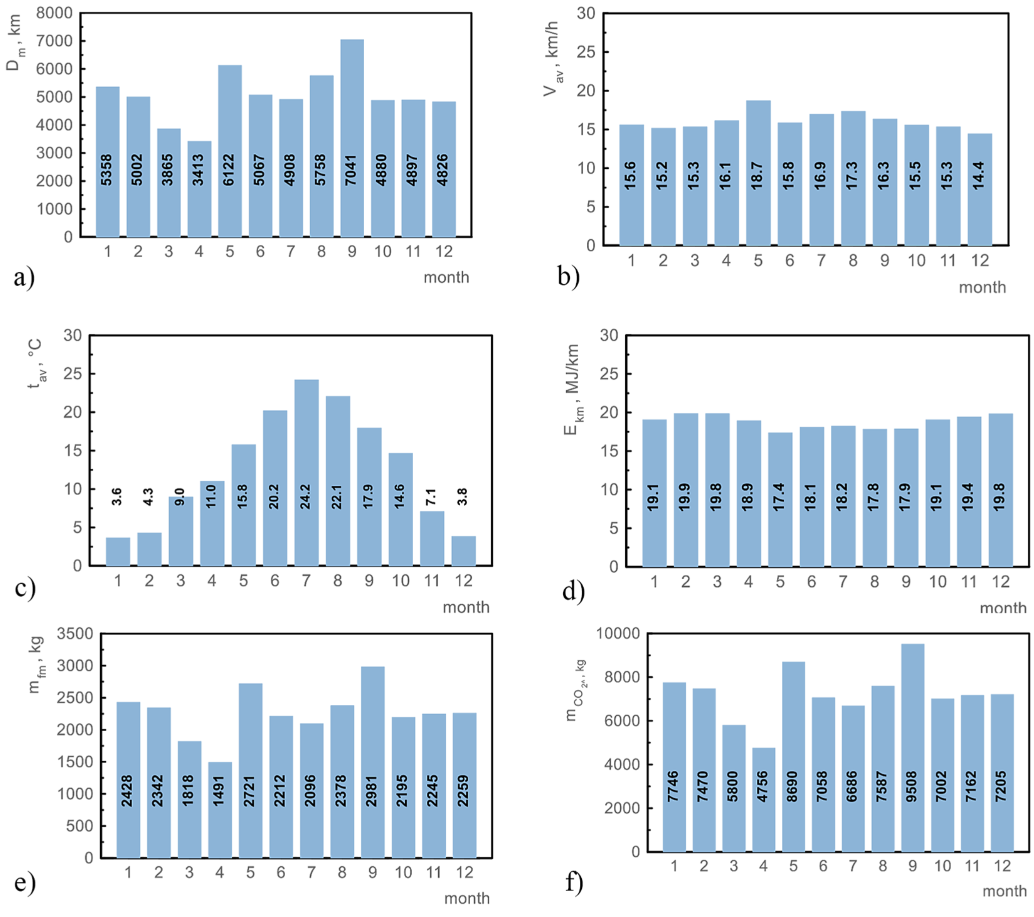

Figure 7. Measurements summarized by month for the entire year of the measurement: (a) distance run by the vehicle per month, (b) average vehicle speed, (c) average temperature in a given month, (d) average energy required to run 1 km, (e) total mass of fuel used in the following months, (d) mass of carbon dioxide emitted in the following months

Table 2 presents the results by year, and it is clear that the bus traveled over 60.000 km and consumed more than 27.000 kg of fuel. The average fuel consumption per day was 98 kg.

The consumed fuel emitted over 60.000 kg of carbon dioxide into the atmosphere. The specified daily fuel mass is 98 kilograms per day. The average vehicle speed is 15.8 km/h, and the average energy consumption is approximately 18 MJ per kilometer. All data are given in Table 2.

The results of the energy consumption contained in the fuel necessary to cover 1 km, expressed in MJ per kilometer are given in Figure 7d. The recorded values range from 17 to 20 MJ/kg. It is clear that the season of year affects the amount of energy necessary to travel one kilometer. The lowest values were registered from May to September when the temperature is the highest in the year, whereas the highest ones were in the autumn, i.e. from November to December and in the winter, i.e. from January to March. Two factors contributed to the increase in energy consumption in the winter, i.e. traffic conditions worsened by rain and snow and the ambient temperature that made the vehicle warm-up time longer. The lower ambient temperatures resulted in a longer vehicle warm-up time, and consequently higher fuel consumption.

Table 2. Results by year

Defined parameter of scope	Value
Fuel mass per year	27.167 kg
Distance per year	61.130 km
CO_2 emission	86.668 kg
Average temperature under operation	13.3 °C
Average fuel weight	98.08 kg/day
Average driving speed	16.05 km/h
Average energy consumption	19.84 MJ/km

The parameters like the energy consumption and average vehicle speed were used for our comparative analysis to specify how the season influences these two parameters (Table 3). The calculations in Table 1 show that the percentage difference referred to the average energy consumption calculated for the entire year is positive in the winter and autumn periods, with its maximum of approximately 5.7% in February. This means that energy consumption is then the highest per kilometer. At the same time, this difference in the spring and summer takes negative values, i.e. from -3 to -7.5% referred to the average value of energy consumption. The case is different if the percentage differences referred to the average speed are analyzed. The calculated average value for the entire year was 16.05 km/h. In this case, positive values ranging from 0.4 to 16% were registered in the summer, which means that the vehicle achieved higher average speeds than the average annual value. In the winter and autumn, the speed was on average from 2 to almost 10% lower than the average annual average. The lowest value was recorded in December exactly when one of the maximum values of energy consumption in relation to 1 km of the distance was also recorded.

The results presented in this way prove that the plans for the use of public transport vehicles

Table 3. Results of the comparative analysis

Month, -	Ekm, MJ/km	Mean Ekm, MJ/km	Difference from the mean value, %	Speed, km/h	Mean speed, km/h	Difference from the mean value, %
1	19,07	18,78	1,55%	15,60	16,05	-2,83%
2	19,86		5,75%	15,15		-5,60%
3	19,84		5,61%	15,32		-4,55%
4	18,92		0,76%	16,12		0,42%
5	17,37		-7,52%	18,69		16,46%
6	18,07		-3,79%	15,83		-1,35%
7	18,23		-2,93%	16,94		5,53%
8	17,82		-5,10%	17,33		7,96%
9	17,86		-4,89%	16,33		1,75%
10	19,07		1,54%	15,54		-3,16%
11	19,43		3,43%	15,32		-4,54%
12	19,83		5,59%	14,43		-10,11%

should take into account months with higher energy consumption so a given vehicle with a higher energy efficiency of the drive system can be used.

Distribution analysis

This stage related to the continued descriptive statistics. Histograms as a count diagram for the step variable were plotted. They are a distributive series of sample results for subsequent features. The results refer to the subsequent measurement days throughout the year. The number of classes k of distribution series was determined from the size sample of approximately 284 (Equation 9). The range was also calculated. Therefore, in accordance with formulas 9, the number of classes was assumed to be 20. The calculations resaults are in Table 4.

$$k = 1 + 3.322 \cdot \ln(n_i) \quad (8)$$

The length of the class interval was determined as the quotient of the range R (Equation 9) divided by the number of classes k (Equation 10):

$$R = x_{max} - x_{min} \quad (9)$$

$$b = \frac{R}{k} \quad (10)$$

The results given in Figure 7 lead to the following observations and conclusions.

Figure 7a shows the frequency distribution of daily distances covered by a city bus in Lublin. The dominant daily distance value is within the range of approximately 200–250 km, which suggests that on most days the bus traveled a distance close to the average of 222 km. The distribution is close to symmetrical, which indicates the stability of bus operations throughout the year. Figure 7b illustrates the distribution of average vehicle speeds. The highest frequency was recorded in the range of 15–20 km/h with an average value of

Table 4. Analysis of the histogram

Parameter	*R*	n_i	*k* calculated	*k* accepted
Distance	405.21	277	19.1	20
Average speed	12.22	277	19.1	20
Fuel mass consumed	150.10	277	19.1	20
Daily average energy consumption	7.75	277	19.1	20

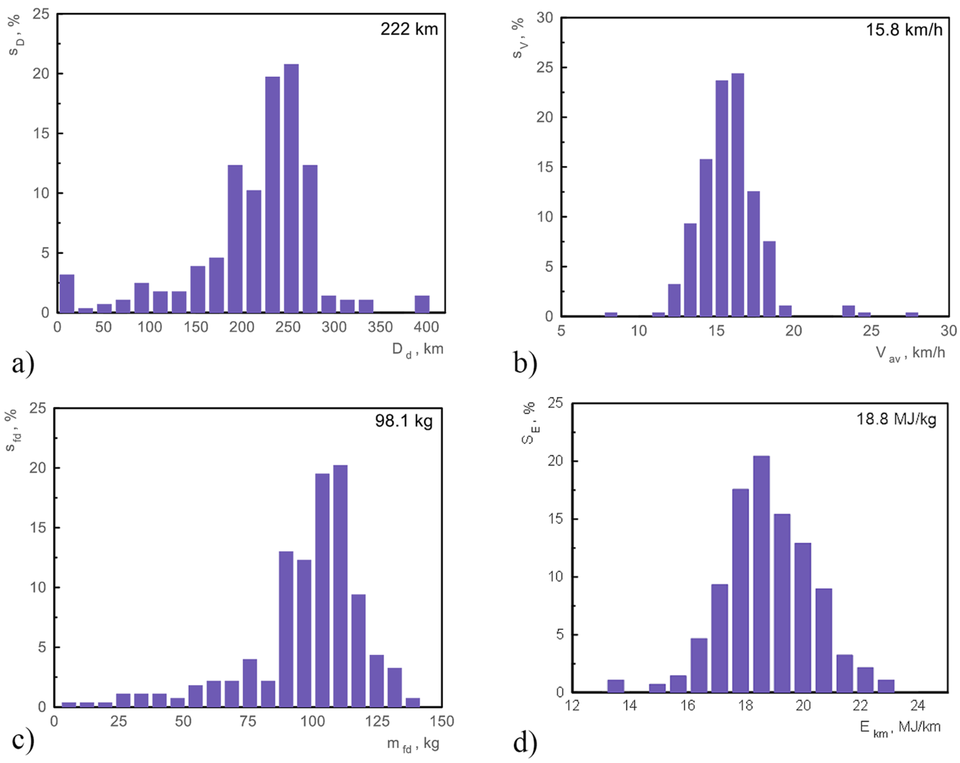

Figure 8. Frequencies of the occurrence of the studied parameters in relative terms (a) daily distance, (b) average vehicle speed, (c) daily mass of fuel consumed, (d) specific energy per kilometer

approximately 16.05 km/h. The data shows that the bus mostly traveled at a speed typical of urban conditions, with frequent stops and heavy traffic. Figure 7c shows the daily mass of fuel consumed by the bus. The most common fuel mass ranges from 75 kg to 100 kg. The maximum value was 140 kg. The distribution characteristics suggest that fuel consumption is closely correlated with daily distance and driving conditions. The last Figure 7d plots the specific energy consumed per kilometer. The values are mainly around 18-20 MJ/kg, with a predominant value around 19.8 MJ/kg. This indicator shows bus fuel efficiency per kilometer. This distribution is close to symmetric, but there is an increased number to the right of the mean value.

The results plotted in Figures 7 and 8 can be used to specify important aspects regarding the operation of a city bus in Lublin. Above all, if the daily distance of approximately 220 km is maintained, the routes of the research bus tend to be regular and repeatable. The average annual vehicle speed is 16.05 km/h and is typical for urban public transport due to bus stops and changing traffic intensity that affects driving speed. The recorded fuel consumption, expressed as the average fuel mass, was approximately 98.1 kg per day. This value can be a reference point to optimize fuel consumption and reduce exhaust emissions, including CO_2. The average fuel energy per kilometer was 19.8 MJ/km. It is a key energy efficiency indicator that can be a reference point for other vehicles and different operation conditions.

The data on other cities and bus fleets shows that the average speed of city buses in Chennai, India, is approximately 17.8 km/h in rush hours and 21.5 km/h in off-peak hours [20]. On the other hand, in Rzeszów, Poland, a Mercedes-Benz O530 city bus reached average speed with driving only on the selected route as high as 23.31 km/h [21]. However, its average speed with stopping time at bus stops was 14.14 km/h, which is lower than in Lublin. The average speed of buses in an urban environment usually ranges from 15 to 25 km/h by road conditions, route characteristics, and stopping frequency [22]. Therefore, the average speed registered in our research is similar to that in other cities.

If the recorded results on the energy consumption, expressed in MJ/km, are compared with the ones discussed in the literature, it should be noted that the range is wide. For example, the fuel consumption of buses with compression ignition engines in China is estimated as only 9.1 MJ/km [23]. Other results are discussed in [24, 25] where the average fuel consumption of buses wih compression ignition engines was 14.6 MJ/km. These are lower values because they apply to buses up to 18.000 kg. The research described in this article applied to a bus with a permissible weight of 28.000 kg. The average consumption recorded in Lublin was approximately 19 MJ/km. However, the report [26] states that energy consumption for a bus with a compression ignition engine can be as high as 18 MJ/km, which is a value similar to our results. However, the energy consumption in a bus ranged even from 24.89 to 36.50 MJ/km [27], which could be due to the larger passenger load and heavy traffic.

DEPENDENCY ANALYSIS

The next stage of the analysis was to quantitatively determine how operating conditions affect the consumption of energy contained in the fuel. The results were expressed in MJ/km. The scope of the analysis included the results for one year.

Firgure 8 shows the relationship between the energy consumption in MJ/km and the vehicle speed, average fuel consumption, expressed as average fuel mass, was approximately 98.1 kg per day. This value can be a reference point in reducing fuel consumption and reducing exhaust emissions, including CO_2. The average fuel energy per kilometer was 19.8 MJ/km and can be a key energy efficiency indicator in relation to other vehicles. These are the results of the analyses for the entire year, and the correlations refer to 284 days of vehicle operation.

Figure 8a shows that a clear linear decrease in energy consumption as the average vehicle speed increases. This is due to the fact that the increased vehicle speed results from less traffic. The slope coefficient of the line is -0.67, which means that each increase in the average vehicle speed by 1 km is accompanied by the unit energy consumption decrease by 0.67 MJ/km. It is also clear that buses on routes in suburban areas consume less energy.

Figure 8 b shows the energy consumption versus ambient temperature. A decreasing relationship was also recorded here because operating the vehicle at higher temperatures results in shorter engine warm-up time and better road conditions. These two factors are behind a reduced energy consumption. The adopted linear regression of

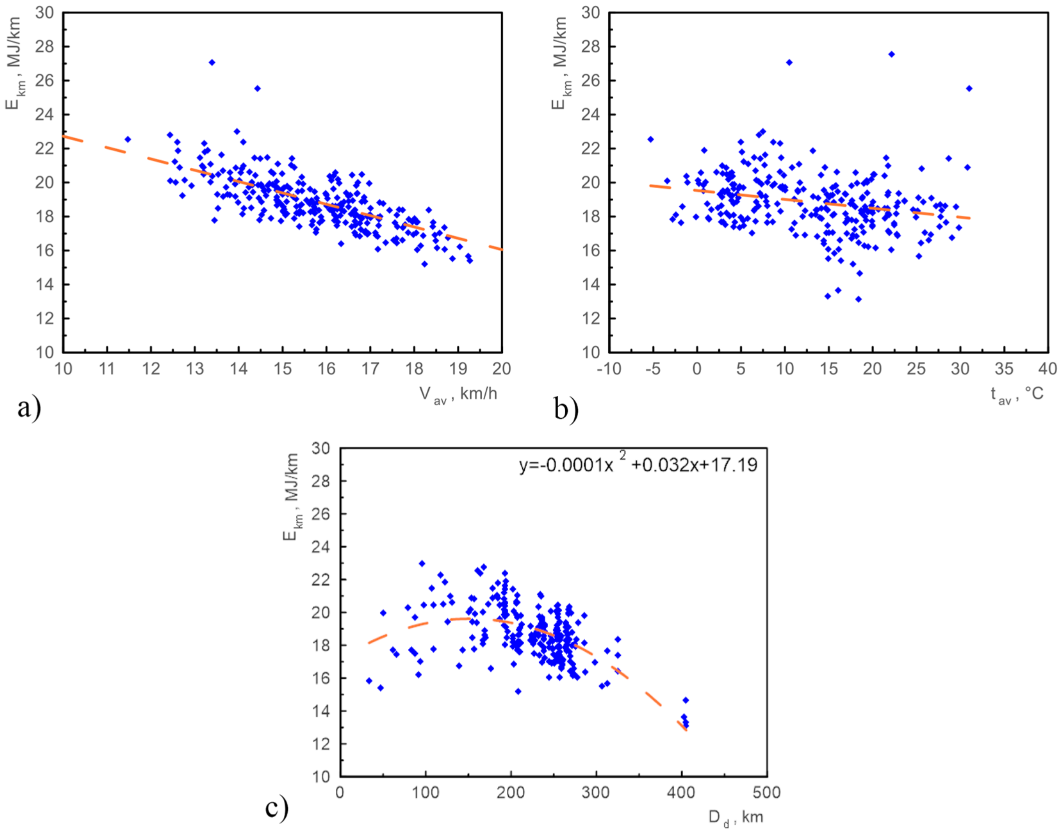

Figure 9. Energy consumption versus: (a) average vehicle speed, (b) average ambient temperature, (c) daily distance

the analyzed correlation shows that each increase in ambient temperature by one degree is followed by an energy consumption decrease by approximately 0.06 MJ km. This difference is not as significant as in the impact of average speed, but the impact of temperature can be clearly confirmed.

Figure 8c shows the correlation between the energy consumption in the fuel and the daily distance. This relationship was described by a quadratic function. The extreme of the function is clear. This is the maximum energy consumption for a distance of approximately 200 meters per day. Energy consumption reduced for shorter and longer than 200 km distances. Such results may be related to the fact that the maximum energy consumption occurred under the highest load conditions. This means that the bus which covered a distance of about 200 kilometers a day on average operated only in morning and afternoon rush hours. This is the time with the highest passenger load and heaviest traffic. The longer daily distance resulting in the reduced energy consumption probably corresponds to the use of the vehicle on routes that also cover suburban sections.

CONCLUSIONS

The research was carried out on a Mercedes Conecto 18 bus in the area of Lublin. The research period was one year. The analyses have provided the data on bus operation under everyday urban conditions. The analysis focused on factors such as fuel consumption, CO_2 emissions, vehicle speed, daily distance and the impact of weather conditions on vehicle efficiency. A summary of the results can be formulated as follows:

- total fuel consumption and carbon dioxide emissions – the research was carried out for 284 days when the bus covered the distance of 60.000 km. The total fuel consumption was 27.000 dm^3 kg of diesel fuel. The average daily fuel consumption was approximately 98 kg. The annual CO_2 emissions amounted to over 86.668 kg of CO_2. The results indicate the significant impact of urban transport on the environment and emphasize the need for a continuous optimization of fuel consumption and the search for alternative sources of propulsion.
- energy efficiency – the analyzed average energy consumption per kilometer was approximately

19.84 MJ/km; these values are subject to seasonal fluctuations due to the impact of weather conditions on vehicle performance. It was noticed that in the winter months with lower temperatures and deteriorating road surfaces fuel consumption increased by almost 6%.
- vehicle speed and ambient temperature – a quantitative correlation between vehicle speed and energy consumption has been defined. The calculations show that if the average speed increased by 1 km/h, the energy consumption per kilometer decreased by 0.67 MJ, and similarly the 1 °C decrease of ambient temperature reduced energy consumption by approximately 0.06 MJ/km.
- daily distance – a daily distance ranging from 200 to 220 km is characterized by the highest energy consumption in fuel. It amounted to a maximum of approximately 21 MJ/km. This was due to the heavy traffic in the morning and afternoon and the large vehicle weight due to the number of passengers on board. These results can be used to plan urban bus timetables in order to reduce fuel consumption costs.
- comparison – the results were compared with the data from other cities and bus fleets. It was shown that the average speed of the tested bus in Lublin is similar to the speeds presented in other works. The determined energy consumption was higher, which may be due to the fact that the research vehicle weighed more, i.e. 28.000 kg. Our bus was 18 m long, whereas shorter buses of 12 m are usually tested.

To sum up, the conducted research provided significant research data on the energy efficiency of urban transport in Lublin and enabled us to define certain key factors behind the consumption of energy contained in fuel.

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