Determining the fuel consumption of a public city bus in urban traffic

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Abstract. The fuel consumption of a public transport bus depends on many factors. Various speeds, acceleration and deceleration modes, stopping times at bus stops and congestion, as well as the load depending on the number of transported passengers have a significant impact on the fuel consumption of the city bus. It is difficult to investigate the influence of these factors on fuel consumption using simple equations to determine the energy efficiency of vehicles. A very useful method in this case is the VSP (Vehicle Specific Power) method. The fuel consumption model based on this method uses a number of parameters. Taking into account the measurement data obtained from the actual mileage of city buses, the relevant parameters of the model were determined. The verified model was used in the process of computer simulation aimed at determining the fuel consumption of the bus in urban traffic. Particular attention was paid to the study of the impact of traffic during rush hours and congestion on fuel consumption. The impact and significance of the selected parameters on the fuel consumption of the city bus were also assessed using computer simulations.

1. Introduction

Urban transport is an essential element for the proper functioning of the city. It satisfies the communication and transport needs of the city's inhabitants. In many cases, the functioning of public transport contributes to environmental pollution with exhaust gases and noise and makes life difficult for residents through congestion [1]. There are many forms of urban transport. Some of them are friendly or indifferent to the environment. Such forms of transport include pedestrian, bicycle, and zero-emission transport. Cycling is highly recommended [2] and is becoming more and more widespread. The second form of transport, which is not neutral to the environment, uses consumables to drive fossil fuels. The share of individual forms of transport in total transport depends on the size of the city and the income of its inhabitants, as well as on the policy of the city authorities and the government. It is impossible to immediately terminate a transport using fossil fuels. Hence, as part of the development of sustainable transport, it is assumed that the forms of transport that are harmful to the environment will be gradually reduced. The ideal solution would be to withdraw all fossil fuel vehicles from use and replace them with zero-emission electric vehicles. Most countries are heading towards this solution. This solution is not cheap. It requires significant financial outlays and solutions to many technical problems related to energy storage. At present, except for a few cases, the share of means of transport using fossil fuels is
dominant. In order not to wait passively for new means and transport technologies, measures are taken to reduce fuel consumption and emissions in environmentally friendly transport. One of the currently implemented measures to protect the environment and reduce pollution include all works aimed at encouraging residents to choose public transport [1] as its main form of transport. Public transport, even the one that uses fossil fuels to drive the bus, is more advantageous from the point of view of energy efficiency and emissions than individual transport by passenger cars. Fuel consumption per passenger in public transport [3] may be several times lower than in individual transport. Other measures taken are aimed at reducing fuel consumption and pollutant emissions in the already operating transport system. Many measures are available in this area. It may be driver training [4] aimed at reducing fuel consumption or applying the priority of transit at intersections for city buses and smoothing bus traffic by using bus lanes [5]. Assessment of the effectiveness of the solutions introduced into the transport system requires an appropriate tool to determine fuel consumption in variable traffic conditions. As part of the work on the basis of the VSP (Vehicle Specific Power) method [3, 6, 7], it was decided to create such a model tool for analyzing the bus traffic parameters and determining fuel consumption. Each city has its own specificity and is characterized by different traffic schedules and vehicle loads. Having data from measurements of traffic volume and data on average fuel consumption, the parameters of the fuel consumption model were first estimated. Then the model was verified. Next, using the verified model and computer simulation process, the determination of fuel consumption in variable traffic conditions prevailing in the city of Rzeszow was started. An extensive monitoring system [8] or a set of GPS receivers can be used to collect data on vehicle traffic. The research carried out in the work is of a preliminary and informative nature. The collected data and the experience gained will be the basis for further comprehensive work related to the functioning of public transport in the city.

2. Operating conditions of urban bus

The operating conditions of the city bus are very unfavorable from the point of view of the energy demand of the vehicle. During the passage of a given route, the vehicle accelerates many times and loses speed to zero. In vehicles with conventional drive, we deal then with the conversion of the kinetic energy of the vehicle into the caloric energy in the brakes. Occurring breaks in traffic are forced by stops at bus stops necessary to replace passengers as well as by unplanned events in city traffic, such as traffic jams or red lights on the route. The influence of the number of passengers getting on and off the bus on the bus stop time is shown in Figure 1. The data presented in Figure 1 come from our own research.

![Figure 1](image1.png)

**Figure 1.** The relationship between the bus stop time and the number of passengers getting on and off.

Figure 2 shows a selected fragment of the route of bus No. 17 with the numbers from 1 to 5 marked with stops and the place where the traffic volume was measured. The place where the measurement was made
is marked with the letter P. The section shown in Figure 2 is a fragment of one of the main city roads. Stops marked with numbers 3, 4 and 5 are located in the very center of the city. Figure 3 shows the hourly distribution of motor vehicle traffic at point P. The presented data relate to vehicles traveling to the east. By 7 a.m., traffic is approaching its maximum. The highest levels of traffic intensity occur between 8:00 and 9:00. The distribution of hourly traffic intensity during the day may be of different nature [9]. It depends on many factors such as the type and time of day and the nature of the street. In the case of the street's character, its function is important: downtown or a typical access road from remote housing estates.

**Figure 2.** A selected section of the 17 bus route with stops and the traffic volume measurement point "P" marked.

**Figure 3.** Hourly traffic of vehicles at the "P" point in the east direction.

With the increase in traffic, the number of unplanned stops increases and the travel time of a given section of the route lengthens. This phenomenon is clearly visible in Figure 4 showing the speed distribution of two selected courses of line "17" as a function of the distance traveled and driving time.

**Figure 4.** Recorded runs on a selected section of the route from 6:26 am and 3:30 pm between stops 1 and 5: a - as a function of distance travelled; b - course from 6:26 am as a function of driving time; c - course from 3:30 pm as a function of travel time.
The bus departure from 3:30 pm is carried out during the traffic rush hour. In the section of the route between stops 3 and 5 through the city center, the bus made an additional 5 stops compared to the morning departure. Another important element in assessing fuel consumption may be the variable load on the bus. Depending on the time of day, the filling of the bus with passengers between stops may be different, as shown in Figure 5. Additionally, early morning and evening departures are characterized by lower transports on the entire route.

![Figure 5. Number of passengers on the bus between stops on the selected working day for line "0B": a - departure at 13:46; b - departure at 15:22.]

Increasing the number of passengers carried increases the load on the vehicle. Taking into account the data from Figure 5 and assuming an average passenger mass of 55 kg, the additional load on the bus for these two journeys varies from 275 kg to 3000 kg. In relation to the mass of the bus 11,000 kg, this represents 2.5% to 27% of the additional load.

3. Methodology of fuel consumption determining

3.1. Movement resistance and energy consumption

The energy supplied to the vehicle in fuel is used to overcome external and internal resistance to motion and to ensure the operation of the vehicle's engine during idle and stops forced by traffic lights or congestion. When stopping, the vehicle's engine drives devices such as the air compressor and alternator necessary for the proper operation of the bus. While moving on a horizontal plane, the vehicle is subjected to external resistance forces shown in Figure 6.

![Figure 6. The system of forces acting on the vehicle on a level road.]

The sum of all these external forces is balanced by the driving or braking force in the case of decelerated motion and is represented by the equation (1). The presented dependence (1) also takes into account the resistance force associated with climbing the hill:
\[ F_n = F_t + F_p + F_b + F_w \]  \hspace{1cm} (1)

The individual components of equation (1) are described by the following relationships:

- \( F_t \) - rolling resistance force.
  \[ F_t = m g f_t \]  \hspace{1cm} (2)

where:  
- \( g \) – acceleration of gravity;
- \( f_t \) – rolling resistance term coefficient;
- \( m \) - gross vehicle mass.

- \( F_p \) - aerodynamic resistance of the vehicle.
  \[ F_p = \frac{1}{2} \rho c_x S v^2 \]  \hspace{1cm} (3)

where:  
- \( \rho \) - ambient air density;
- \( S \) - frontal area of the vehicle;
- \( c_x \) – air drag coefficient;
- \( v \) – speed.

- \( F_b \) - inertia force.
  \[ F_b = ma \]  \hspace{1cm} (4)

where:  
- \( a \) – acceleration.

- \( F_w \) - slope force.
  \[ F_w = m g \sin \alpha \]  \hspace{1cm} (5)

where:  
- \( \alpha \) - angle of slope.

The total demand for energy supplied in fuel by the bus is described by the relationship:

\[ E_T = E_1 + E_2 \]  \hspace{1cm} (6)

where:  
- \( E_T \) – total energy;
- \( E_1 \) – energy necessary to overcome external resistances provided by the engine;
- \( E_2 \) – energy consumed by the engine when the bus is stationary.

\[ E_1 = \int_0^{l_e} \frac{F_n}{\eta_m} \, dl \]  \hspace{1cm} (7)

where:  
- \( l_e \) - distance travelled by the bus;
- \( \eta_m \) - mechanical efficiency of the drive system.

Direct calculation of fuel consumption under varying traffic conditions of the equation (7) can be subject to large errors. The energy efficiency of the motor is not constant. It depends on the parameters of its work, such as the torque \( T_e \) and the angular speed of the motor shaft \( \omega \). Therefore, with this method, it is necessary to know exactly the external characteristics of the engine. The engine operation parameters can be determined from the dependencies (8) and (9):
\[ T_e = \frac{F_{nr}d}{i_b i_g \eta_m} \]  
\[ \omega = \frac{vi_b i_g}{r_d} \]

where:  
- \( i_b \) – gear ratio;  
- \( i_g \) – final drive ratio;  
- \( r_d \) – dynamic radius of the wheel.

The range of \( T_e \) and \( \omega \) changes during the bus movement is quite large [10]. The energy efficiency of the engine is subject to major changes [11]. This makes the calculation of fuel consumption much more difficult.

### 3.2. The VSP method

Determining fuel consumption on the basis of the previously described methodology is quite complicated. A much simpler way is to determine the fuel consumption using the VSP method. This method is used not only to determine fuel consumption [6,7,10] but also to determine the emission of harmful substances into the environment [12,13,14,15,16]. Various factors related to the movement of the vehicle affect the amount of fuel used during the actual work cycle of the vehicle. First, these are speed, acceleration and road gradient. In the case of large changes in the number of passengers transported, fuel consumption is also influenced by the variable load on the bus [12, 13, 15]. The VSP method is based on determining an index called \( VSP \), which takes into account aerodynamic drag, tire rolling resistance and road gradient. \( VSP \) shows the power per unit mass of the vehicle and is a function of the vehicle speed, acceleration and gradient. The \( VSP \) index can be determined using the equation (10):

\[ VSP = \frac{F_t + F_p + F_b + F_w}{m} v \]  

(10)

Taking into account the equations from (2) to (5), the following transformations are obtained from the equation (11):

\[ VSP = \left( g f_t + a + gsina + \frac{1}{2} \rho c_x S v^2 m^{-1} \right) v \]  

(11)

The unit of the \( VSP \) index is Wkg\(^{-1}\) or, what is more common, and the same as \( \text{m}^2\text{s}^{-3} \). An exemplary \( VSP \) plot as a function of time, ranked from the lowest to the highest, is shown in Figure 7. An important activity in the \( VSP \) method is to determine fuel consumption \( q \) (gs\(^{-1}\)) as a function of the \( VSP \) index. Most often it is done on the basis of the results of experimental research and the performed statistical analysis. An exemplary course of fuel consumption \( q \) in the \( VSP \) function is shown in Figure 8.
Figure 7. Dependence of VSP on time

Figure 8. Dependence of fuel consumption $q$ on time

Another important step in the VSP method is to determine the intervals in which the number of samples will be counted. An example of such a definition of intervals is shown in Table 1.

Table 1. Definition of VSP ranges

| VSP number | VSP range (m$^2$s$^{-3}$) | VSP number | VSP range (m$^2$s$^{-3}$) |
|------------|---------------------------|------------|---------------------------|
| 1          | $VSP \leq 0$              | 8          | $6 \leq VSP < 7$          |
| 2          | $0 \leq VSP < 1$          | 9          | $7 \leq VSP < 8$          |
| 3          | $1 \leq VSP < 2$          | 10         | $8 \leq VSP < 9$          |
| 4          | $2 \leq VSP < 3$          | 11         | $9 \leq VSP < 10$         |
| 5          | $3 \leq VSP < 4$          | 12         | $10 \leq VSP < 11$        |
| 6          | $4 \leq VSP < 5$          | 13         | $11 \leq VSP < 12$        |
| 7          | $5 \leq VSP < 6$          | 14         | $12 \leq VSP$             |

Using the dependence (12), it is possible to finally determine the fuel consumption from the VSP course shown in Figure 7.

$$Q = \sum_{i=1}^{14} q_i t_i \text{ (g)}$$ (12)

where: $Q$ - total fuel consumption for a given driving cycle;
$q_i$ - energy consumption rate for the VSP range $i$;
$t_i$ - time spent on VSP mode $i$ for a given driving cycle.

The accuracy of determining fuel consumption in the VSP method depends on the accuracy of determining the relationship from Figure 8. A careful process of model calibration and determining the curve from Figure 8 will cause the relative error between the measured and calculated values to drop to a few percent [12].

4. Simulation calculations using the VSP method

In the process of simulating fuel consumption it was assumed that the bus carried 30 passengers between the stops. The empty mass of the bus was 11,000 kg. After taking into account the number of transported
passengers, the bus mass used for calculations was 13,000 kg. The simulation tests of fuel consumption concerned the 0B bus. The 9.4 km bus route is shown in Figure 9. On the entire 0B bus route, there are 19 stops at which the bus must stop. In addition, there are several crossings and pedestrian crossings with traffic lights on the route. While the vehicle was moving and stationary, all data from the GPS receiver was read and recorded. Figure 10 shows a fragment of a sheet with recorded data. The entire file contains data on 17 courses between 7:30 and 20:00.

In the simulation process of fuel consumption, the drag force $F_w$ related to climbing the hill was omitted. For the "0B" bus route under analysis, the minimum height above sea level was 199 m and the maximum 211 m. The error resulting from the omission of the force $F_w$ in the fuel consumption calculations is very small. Larger errors are generated by not taking the bus variable into account. Figure 11 shows the speed profile of the 0B bus between 7:30 am and 8:00 pm. These data concern all 17 routes and are very dense, which makes bus stops practically invisible. These stops may be related to stopping the bus at a bus stop, stopping in traffic or stopping with the engine off at the final stop of the route.

In the data file used for the simulation tests, the records concerning the stop of the bus at the final stop of the route with the engine turned off have been removed. From the file processed in this way, the speed distribution $v$ and the distribution of calculated accelerations were determined, as shown in Figure 12. Stops and speeds below 5 km/h constitute the largest part of the bus working time. Delays, on the other hand, take greater values than accelerations. Acceleration rarely exceeds 1 m/s$^2$.
Figure 12. The distribution determined from the entire active driving cycle; a - speeds, b - accelerations.

Using the relation (11), VSP indices were determined, and their values were ranked from the lowest to the highest. Such an ordered sequence of VSP indicators is shown in Figure 13. In accordance with Table 1 and on the basis of the diagram in Figure 13, the frequencies of the occurrence of samples in individual VSP ranges were determined. The last step before determining fuel consumption from dependence (12) was to determine the relationship between fuel consumption \( q \) and the VSP index. For this purpose, the measured value of the average fuel consumption during the day was used, amounting to 43.2 L/100 km, and data from the works [7, 10, 11, 14]. The course of the determined relationship is shown in Figure 14. When determining the relationship \( q = f (VSP) \), an important criterion was the minimization of the error described by the equation (13):

\[
\Delta Q = Q_m - Q_e
\]

where: \( \Delta Q \) – error in determining the fuel consumption; 
\( Q_m \) – measured fuel consumption value; 
\( Q_e \) – calculated fuel consumption value.

Figure 13. VSP dependence on time in the tested cycle. 
Figure 14. Dependence of fuel consumption \( q \) in the tested cycle.

In order to determine the fuel consumption in individual courses carried out on a given working day, it was necessary to separate the values concerning these courses from the data sheet. For each course, the VSP index had to be calculated and the frequency of occurrence of the calculated index in particular
ranges had to be determined. Then, using the equation (12) and the relationship from Figure 14, fuel consumption was determined for all courses. The calculated fuel consumption values for 17 journeys as well as the average speed values from the given journeys are shown in Figure 15.

![Figure 15](image)

**Figure 15.** Values determined for individual bus trips on a selected working day; a - fuel consumption, b - average speed over the distance traveled.

In Figure 15 it can be seen that practically each course has different fuel consumption, as well as a different average speed.

5. Analysis of the results of simulation calculations

The data shown in Figure 15 clearly show the significant impact of the afternoon traffic rush hours on fuel consumption and average speeds. The highest total fuel consumption is for journeys between 13:00 and 16:00. These hours are the afternoon rush hours. During these hours there are the lowest average speeds reached by the bus on the entire route. On the other hand, the trips between 9 and 12 hours are characterized by the lowest fuel consumption and high average speed. Average speed is directly related to the total journey time including traffic and stops. Figure 16 shows how the total travel times changed during the day. For the total travel times greater than 30 minutes, it can be concluded on the basis of Figure 17 that fuel consumption largely depends on the travel time. However, there are courses with a similar total duration of approximately 39 minutes but with different fuel consumption. The fuel consumption determined for the course from 12:40 hours is \( Q = 3269 \text{ g} \), which is 42.41 L/100 km. For the course from 15:42, fuel consumption \( Q = 3443 \text{ g} \), which is 44.66 L/100 km, so it is about 5% higher.

![Figure 16](image)

**Figure 16.** Duration of individual courses during the day.

![Figure 17](image)

**Figure 17.** Fuel consumption depending on the duration of the course.
The analysis of selected values such as $v$ and $VSP$ for these courses showed differences in the courses of these values. Comparing figures 18a and 18b with each other, it can be seen that in the case of a journey from 3:42 PM, the speed of the bus is much more frequent in the range of 50 - 60 km/h. The comparison of Figures 18c and 18d presenting the velocity histograms $v$ shows the scales of differences in the frequency of achieving higher speeds. The differences are especially noticeable in the speed range 50 - 55 km/h. With the same vehicle mass and other coefficients related to the resistance to motion, the fuel consumption is determined by the $VSP$ index and its distribution. For the 3:40 pm course, Figure 18f has a higher frequency of samples in $VSP$ intervals marked with numbers from 4 to 8. This is probably the difference in the total fuel consumption on a given route. In the histograms from Figures 18e and 18f, the intervals in which $VSP \leq 0$ were omitted.

Figure 18. Selected runs from two different courses; a – speed course departure time 12:40, b - speed course departure time 15:42, c - speed histogram departure time 12:40, d - speed histogram departure time 15:42, e - $VSP$ histogram departure time 12:40, f - $VSP$ histogram departure time 15:42.
For journeys of less than 30 minutes in the evening hours, fuel consumption is also significant. These courses have the highest average speeds and therefore the shortest travel times. As can be seen in Figure 11, in both courses after 18:30, the bus speed is quite often reached in the range of 60-70 km/h. The necessity to stop the bus and stop at all stops causes a large loss of kinetic energy of the moving bus. The kinetic energy of a bus traveling at 70 km/h is almost double the kinetic energy of a bus traveling at 50 km/h. An additional factor influencing the obtained high fuel consumption results may be the assumption of a constant total bus mass in all simulation calculations. In the evening journeys, the number of passengers transported throughout the course is 20 to 40% lower than the transport between 7:00 am and 5:00 pm. After considering the drop in load, the final simulation result may be slightly reduced.

6. Conclusion
The developed model has proved to be useful for the analysis of the influence of variable traffic conditions on fuel consumption assuming a constant or slightly changing total vehicle mass. The fuel consumption values obtained in the simulation process take into account the influence of factors such as stopping times and speed distributions, with particular emphasis on the maximum speeds achieved. The determined dependence of the specific fuel consumption \( q \) and its course on the basis of the average daily fuel consumption on a given line does not differ from the results presented in the works [7, 14]. However, the developed model requires further work. As part of this work, it will be necessary to examine the impact of large changes in the bus load on the obtained fuel consumption results. In the process of model calibration and verification, data obtained from different days and months should be used. Bus traffic data for different days and months have different loads due to the number of passengers transported and different fuel consumption. The changes in the vehicle load are also important when comparing the rates from the traffic peak with the rates in the early morning and evening hours. After analyzing the recorded measurement data, it also seems necessary to select the measurement equipment more carefully. This is especially true for GPS receivers. The acceleration determined on the basis of GPS measurements in many cases reached the value of \( a > 2 \text{ ms}^{-2} \). This value is unrealistic for a city bus with passengers and results only from random errors in measuring the position of the vehicle. The maximum accelerations obtained by the bus do not exceed the value of \( a = 1.1 \text{ ms}^{-2} \) [11].

7. References
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