Modeling research of city bus fuel consumption for different driving cycles

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Abstract. Simulation studies can be used to determine the fuel consumption and carbon dioxide emissions of city buses. The operating conditions of such vehicles are characterised by a very high variability of vehicle speed due to the large number of stops along the route of the bus. During vehicle testing, driving cycles are used to replicate the real-world conditions and to achieve repeatable test conditions. Such a driving cycle is a profile of speed represented as a function of time or as a function of distance. The speed profile over time can be an advantageous determinant, based on laboratory tests, for estimating fuel consumption and pollutant emissions of city buses. The research subject of this paper was the simulation of bus driving under simulated urban traffic conditions, carried out by means of the VECTO software. VECTO is a tool designed to perform the calculations of fuel consumption and carbon dioxide emissions of vehicles. It enables to model the powertrain of trucks and buses and to carry out simulations on various routes defined by driving cycles. The test object was a mega class bus, equipped with a 225 kW engine. The bus has three axles, including the rear drive axle. The scope of research included four cycles: urban, interurban, urbandelivery and interurban. Each of these was analysed in terms of speed and road gradient. The aim of this work was to perform a simulation study of the effect of the vehicle traffic conditions on the amount of CO₂ emitted and fuel consumption. The obtained results were analysed.

1. Introduction
Fuel consumption and the resulting emissions of toxic exhaust components are constantly being analysed, and efforts are made to reduce these indicators. The indicator relating to the energy required to cover 1 km is also defined. According to the authors of the document describing the “European Green Deal” [1], for a bus it should not exceed 1 kWh/km. As it is known, the amount of carbon dioxide emitted by the engine is directly proportional to the fuel consumed and amounts to 2.6 kg for every kg of ON. This is due to the chemical composition of the fuel molecule, i.e. the amount of hydrogen and carbon. The conducted research has shown that the CO₂ emissions expressed in kg/km depend on operating conditions and can increase by 50%.

The energy efficiency of vehicles, including buses, is also a very important marketing factor. Keeping the product on the market and ensuring its competitiveness are the factors that contribute to the development of the techniques that reduce emissions and fuel consumption [2]. This efficiency is included in the Total Cost of Ownership (TCO). In this case, diesel buses are still competitive. Hybrid buses are not expected to be superior in this regard until 2030 [3].
One way to determine these emissions expressed in g/km and fuel consumption is to conduct road tests using the equipment that allows real-time measurement of emitted compounds and fuel consumption. Exemplary studies concerning this subject and the influence of the way of operation have been included in works [4-6]. There are also works, where the emission is measured under engine dynamometer conditions [7]. This makes it possible to obtain the information on the anticipated emission and fuel consumption already at the stage of power unit design. It is worth mentioning that research procedures, apart from top-down speed profiles, such as the SORT2 cycle, also recommend carrying out such measurements under the actual urban conditions. They are not determined and are characterised by stochasticity. However, the results obtained in this way by some researchers are described as more reliable in comparison with those made on specially prepared test tracks and after strictly specified speed over time [4]. In the case of passenger vehicles and LDVs, the European Union has already taken steps in 2015 to verify emissions under on-road conditions [8]. Such a procedure will be an important complement of the existing laboratory certification of vehicles with road tests under larger real-world conditions. Work is also underway to create new driving cycles that reflect road conditions. Such a description of the work has been included in the article [9]. The article discusses the emission test drive cycle of heavy-duty public transport bus engines. The actual continuous operation mode was divided into 1625 micro-trips. According to the authors, the developed cycle named W1900 better represents the road simulation than the European Transient Cycle (ETC).

Vehicle tests in this area are also carried out under road conditions. Such an approach was presented by the authors of the study [10]. For this purpose, tests were carried out under urban conditions on a predefined route. The object of the research was a vehicle equipped with an LPG system. ON the basis of the information obtained from the EOBD diagnostic system, the authors verified the correctness of the configuration of the installed LPG system, which directly translates into the fuel consumption of the vehicle.

Work is also underway to analyze the impact of operating parameters on fuel consumption. The measurement results presented in [11] define important operational functions, which allows for further conversion of the obtained data in order to measure the fuel consumption in the laboratory. A methodology for measuring fuel consumption based on the actual operating conditions in the city of Žilina and its vicinity was proposed.

Another way to determine emissions and fuel consumption is simulation. This approach has been presented by the authors of works [12-14]. It is also a correct way for this type of assessment. Such examples of software are AVL Cruise or VECTO. VECTO is software developed for the European commission and will be used to determine the CO₂ emissions and fuel consumption of heavy duty vehicles (trucks, buses and coaches) with a gross vehicle weight of more than 3500 kg. Scania believes that VECTO will be an important tool from a sales perspective, so it is essential that it can be integrated smoothly into the sales process. In a sales situation, it must be possible to provide the CO₂ information for HDV specifications faster than VECTO is currently able to do [2]. A new procedure for determining the CO₂ emissions and fuel consumption of individual HDVs has been introduced. Commission Regulation (EU) 2017/2400 sets out a methodology, based on the VECTO tool, by which the CO₂ emissions and fuel consumption of all HGVs and buses can be simulated. This methodology allows taking into account the diversity of the heavy vehicle sector and the high degree of personalisation of individual heavy vehicles. As a first step, from 1 July 2019, CO₂ emissions are determined for four groups of heavy vehicles, which account for around 65-70% of all vehicle CO₂ emissions within the European Union. [15]. One example of such vehicles are city buses, which are still powered by diesel engines in more than 50% [16].

The aim of this work was to perform a simulation study of the effect of vehicle traffic conditions on the amount of CO₂ emitted and fuel consumption. The research made it possible to explain how the traffic volume of vehicles and road conditions, i.e. road inclination, affect the load of the internal combustion engine of a city bus.
2. Methodology

2.1. Object of research
The object of research was a bus of mega class. It is a low-floor vehicle with the total mass without passengers in the range 12700÷15500 kg and length from 15 to 24 m. The allowable total weight including passengers of such a vehicle should not exceed 28000 kg. The classification of buses is specified by the EU regulations contained in the Directive 2001/85/EC and the Regulation of the Minister of Infrastructure of 31 December 2002. An exemplary bus of this class is Solaris Urbino 18 or Mercedes Conecto 18 (Fig. 1). Figure 2 presents the external characteristic of the engine.

![Mercedes Conecto 18 city bus](image1)

![External characteristics of the 225 kW diesel engine](image2)

The selected Mercedes Conecto bus was treated as representative because vehicles of this class from other manufacturers are characterized by similar values of the permissible weight and engine power.

2.2. Methods – software and research scope
The vehicle model used to calculate fuel consumption was developed in software called VECTO. VECTO is a tool designed to perform calculations of fuel consumption and carbon dioxide emissions of vehicles. It enables to model the powertrain of trucks and buses and carry out simulations on different routes defined by driving cycles. The software is written in C language. Each module, i.e. vehicle engine or gearbox, has a separate graphical user interface (Fig. 3).

These types of vehicles are powered by compression ignition engines with a power output of more than 200 kW. The data of the 225 kW engine was used for the calculations. These were power, torque and fuel consumption. Figure 2 shows the speed characteristic curve, which was developed on the basis of data contained in the VECTO software. It shows the relation between power and torque as a function of rotational speed. This dependence is directly proportional to the rotational speed of the crankshaft and does not depend on the engine load for a given rotational speed. The bus is equipped with an automatic six-speed transmission.

The software allows the input of driving cycles that determine vehicle speed and road gradient as a function of time or distance travelled. During the simulation, the engine speed and torque are calculated on the basis of the given conditions of vehicle motion, i.e. speed and acceleration. On this basis, the fuel and energy consumption is calculated.

It should also be emphasised that VECTO is an open, publicly available software, which was developed by the European Commission and its Joint Research Centre as the main source of CO₂ emissions in the European Union. The VECTO software includes the database with fuel consumption characteristics of compression ignition engines. These are engines used in city buses and heavy goods vehicles. Driving cycles such as SORT or EUDC are time series of vehicle speeds recorded at consecutive (equally spaced) time points [17-18]. It represents a typical driving pattern of a city bus within a city. Vehicle speed profiles are an important input to state-of-the-art computational models of
vehicle emissions and energy consumption. The test is the result of a synthesis of real-world driving conditions, i.e. speed, acceleration or road gradient. [19-21]. Vehicle manufacturers use driving cycles in vehicle design, certification and marketing. The speed profile over time can be a beneficial laboratory-based proxy for estimating fuel consumption and emissions of city buses [20-21]. The Vecto software contains several tests that are dedicated to the simulation of urban bus driving. These tests are urban, suburban, urbendelivery, interurban. Each of them contains the information about current speed, stopping time and slope of the road. The tests were conducted for the above-mentioned four tests. Speed profiles are included in the figures below. These are the changes in speed over time. The calculations were carried out for four driving cycles: urban, urbendelivery, suburban and interurban. The cycles reflected the traffic conditions of an urban bus, i.e. varying speed and road gradient. These values affected the vehicle's resistance to motion, which in turn directly affects fuel consumption.

The first driving test that was used is called Urban. This is a test the speed and road gradient of which is given in the Vecto software. The driving time in this case is about 7000 s. The distance covered by the vehicle is 39 km. The maximum speed is 60 km/h, while the average speed is 17 km/h. The speed profile shown in Figure 4 is characteristic of a city bus. The gradient of the road assumed for the calculation varies from -8 to 8%.

Figure 3. Graphic interface of the Vecto software: a) main module, b) vehicle module, c) engine module, d) gearbox module.
The next driving test is UrbanDelivery. In this case, the driving cycle lasts almost 9000 s. In this time the bus covers about 74 km. The average speed of the vehicle is 26 km/h and the maximum is 85 km/h. The determined frequency of occurrence of individual vehicle speeds shows a distribution close to symmetrical shape. The slope of the road varies from -6 to 6%.

The third test that was used in the calculations is called Suburban. The driving time in this case is approximately 2100 s. The distance covered by the vehicle is 23 km. The maximum speed is 55 km/h. The determined time density of the vehicle speed in this cycle is characterised by the highest percentage of speed in the 25-35 km/h range, similar to the Urban cycle. However, there is a difference for the road gradient, which, assumed for the calculation, varies from -3 to 3%.

The last test that was simulated is the InterUrban cycle. This cycle lasts approximately 1000 s. The distance covered by the vehicle is 97 km. The average speed is 35 km/h and the maximum speed is 76 km/h. While covering the road in the first half, this cycle is characterised by small changes in road gradient ranging from -2 to +2%. In the second part, the values temporarily reach even 10%.

3. Results and analysis

Figure 5 shows the results of calculations in the form of time courses of the fuel mass flow rate for consecutive assumed driving cycles. It can be seen that the fuel consumption ranges from 0 for engine braking to about 45 kg/h for maximum speed. Obviously, the fuel consumption depends on the vehicle speed and is highest for the UrbanDelivery and InterUrban cycles. The maximum fuel consumption obtained during the Urban and Suburban cycles are typically urban cycles; hence, the high process variability and lower speeds. In these two cases, the mass flow of fuel did not exceed 30 kg/h. The following table summarises the extracted results in terms of distance travelled, average speed, etc.
Figure 5. Fuel mass flow rate for each driving cycle.

For each driving cycle was calculated an integral marked from fuel consumption where the limits of integration are as follows: \( t_1 = 0 \) and \( t_2 = \) time of cycle in seconds.

\[
f_T = \int_{t_1}^{t_2} m_{\text{flow}} \, dt
\]  

(1)

where:
- \( f_T \) – total fuel consumption [kg],
- \( m_{\text{flow}} \) – fuel consumption per hour [kg/h],
- \( t \) – time [s].

Table 1. Results of fuel consumption calculations.

| Drive cycle     | Distance [km] | Time [s] | Max. speed [km/h] | Average speed [km/h] | Total fuel cons. [kg] | Av. fuel cons. [kg/km] | Total CO\(_2\) emission [kg] |
|-----------------|---------------|----------|-------------------|----------------------|---------------------|------------------------|----------------------------|
| Urban           | 39.95         | 7011     | 59.95             | 17.09                | 16.78               | 0.420                  | 43.63                     |
| UrbanDelivery   | 74.85         | 8888     | 85.03             | 26.62                | 26.65               | 0.356                  | 69.29                     |
| SubUrban        | 23.50         | 3157     | 56.06             | 23.38                | 8.47                | 0.360                  | 22.02                     |
| InterUrban      | 69.92         | 8888     | 86.05             | 35.39                | 27.11               | 0.388                  | 70.49                     |

The results of the average fuel consumption expressed in kg/km presented in Table 1 do not show the influence of the average or maximum speed of the bus. The average fuel consumption is also an
indicator of the energy demand for covering 1 km of the road by the bus. Assuming that 1 kg of diesel fuel corresponds to 11.94 kWh of energy contained in the fuel, we obtain from 4.24 to 5.02 kWh/km. Relating these values to the required 1 kWh/km of mechanical energy, the efficiency of the powertrain in the form of the engine, torque converter and transmission must be taken into account. Carbon dioxide emissions are directly proportional to the mass of fuel consumed during the test and ranged from 22 to 70 kg. This can also be represented as an indicator, which is around 1 kg CO₂/km.

In the case of total fuel consumption, this is obviously dependent on the distance travelled, which varied considerably for the driving cycles used in the calculations. However, it should be noted that the fuel consumption and carbon dioxide emissions are very strongly influenced by the number of vehicle accelerations during the test. Therefore, the highest consumption expressed in kg/km was recorded for the Urban test, which is characterised by the highest number of vehicle accelerations. This is due to the simulation of urban traffic, which is characterised by high intensity and traffic jumpy. The InterUrban cycle is second in terms of consumption, also reflecting the urban traffic conditions. In contrast, the SubUrban and UrbanDelivery cycles reflect the suburban bus routes. In this case, the fuel mass intensity (Figure 6) reaches lower values, ranging between 20 and 30 kg/h. In addition, UrbanDelivery also includes two vehicle stops during which the engine is idling. This also resulted in lower fuel consumption. Similarly, the carbon dioxide emissions are proportional to the fuel consumption.

4. Conclusions

In conclusion, the work carried out on modelling the fuel consumption and carbon dioxide emissions shows that the VECTO software correctly reflects the impact of vehicle motion conditions (occurrence of external resistance) on fuel consumption. The calculations showed that the greatest influence on the energy demand is exerted by the number of vehicle stops along the route, i.e. stops and driving in traffic jams. This is due to the fact that re-accelerating the bus requires overcoming the inertia resistance of the vehicle. In this case, the amount of traffic determines how fast the vehicle accelerates, which limits the driver's ability to drive economically. On the other hand, when there are stops and less vehicle stops, fuel consumption is lower. At the same time, it should also be noted that the Urban cycle is characterised by the largest range of road gradient changes. The generation of additional potential energy results in increased fuel consumption. The energy stored in the mass of the vehicle can be recovered, as is the case with hybrid vehicles.

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