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*Mirosław WENDEKER*
*Łukasz GRABOWSKI*

**Combustion Engines**
**Polish Scientific Society of Combustion Engines**

# Investigations of the city bus powertrain efficiency

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*Research work on the energy efficiency of vehicles is driven, among other things, by limits related to fuel consumption and carbon dioxide emissions. This also applies to city buses, where fuel consumption averages between 25 and 30 dm$^3$ per 100 km, which can be converted into approximately 87 kg CO$_2$ per dm$^3$. This article, therefore, presents the results of a study of the total efficiency of the power train of a city bus, taking into account the internal combustion engine, transmission, torque converter, and tire friction on the rollers. The test object was a 12-metre city bus equipped with diesel engines and an automatic gearbox. The tests were carried out on a chassis dynamometer by implementing the World Harmonized Vehicle Cycle (WHVC). The WHVC driving test is a synthesis of the vehicle's on-road speeds and consists of three stages: Urban, Rural, and Motorway. During the tests, the fuel consumption, vehicle speed, and power generated at the wheels of the bus were recorded. From this, efficiency was calculated as the ratio of the power measured at the wheels of the bus to the power contained in the fuel supplied to the engine. Efficiency was shown to range from 5 to 22%.*

Key words: *efficiency, city bus, diesel engine*

## 1. Introduction

The efficiency of a vehicle's powertrain depends mainly on the design and efficiency of the engine, drivetrain i.e. gearbox, and main transmission [9, 14]. Despite the limitations associated with plans to phase out internal combustion engines from transport, research is still being carried out in this area [9, 10]. Modern compression-ignition engines are characterized by high thermodynamic efficiency due to, among other things, the use of high-pressure fuel injection systems, turbocharging, and emission control systems [1, 13]. The gearboxes are usually automated gearboxes whose control algorithms are adapted to the optimal engine operating conditions. In addition, the efficiency of the fuel energy conversion process on board the bus is influenced by the resistance to motion of the vehicle operating in urban conditions, i.e. the uphill resistance and inertia resistance, which will contribute to changes in the kinetic and potential energy of the vehicle. Consequently, the internal combustion engine installed as the vehicle's source of propulsion operates under varying load conditions. This is due to the varying intensity of vehicle traffic or the slope of the road. At the same time, the manner of operation has a significant impact on fuel consumption [15], and in particular the driving technique, i.e. the way the accelerator lever is operated.

These factors affect average fuel consumption. This is because, under road conditions, the engine operates at different overall efficiencies. Therefore, some studies have proposed a methodology for applying dynamic correction factors to steady-state engine data. Example results are included in the paper [7]. It was shown that, in the case of a conventionally powered vehicle, the average difference between the real-world energy demand and the values obtained for a vehicle operated in Switzerland was approximately 22% more than during the running test.

Regarding the compression-ignition engine, it should be mentioned that processes such as acceleration, start/stop and cold-start systems must be considered when determining efficiency. Another important factor influencing the transient operation of an IC engine is the turbocharger lag [5, 8].

Under steady-state conditions, the only parameters on which the actual value of the efficiency of converting fuel energy into mechanical power depends are the crankshaft speed and the torque generated by the engine, representing the engine loads. In the case of urban autobahn operation, the resistance to motion is constantly changing. The only state that can be considered a steady state is engine idling. Engine idling can comprise up to 45% of the total operating time of a city bus [2]. However, in the case of transients, characterized by varying engine load and crankshaft speed, the engine efficiency may be lower than that specified by steady-state characteristics.

One method of transient vehicle testing is the use of drive cycles. This is a repeatable representation of the road load conditions mapped. Examples include the popular driving cycle, SORT (Standardised On-Road Tests cycles) [4], or WHVC (World Harmonised Vehicle Cycle). These are time series of post-run speeds recorded at consecutive (equally spaced) time points [11]. They represent typical vehicle driving patterns in urban and non-urban conditions. Driving cycles are the result of a synthesis of real-world driving conditions such as speed, acceleration or road gradient. Driving cycles are often used in vehicle tests on a chassis dynamometer. Thanks to the controlled loading of the vehicle, it is possible to carry out repeated tests, e.g. on exhaust emissions. This allows emission tests to be carried out and compliance with exhaust emission standards to be assessed, which is still the subject of developmental research in internal combustion engine vehicles.

The World Harmonized Heavy Vehicle Cycle test was also used to measure emissions. The formaldehyde (HCHO) emissions from heavy diesel vehicles (HDVs) were presented in the work [11]. The purpose of using the WHVC test is to evaluate HCHO emissions from HDVs under controlled laboratory conditions and compare them with other test cycles, such as the Harmonized Light Vehicle The WHVC test was performed at different temperatures (5°C and 23°C) to evaluate the impact of ambient temperature on HCHO emissions This study aimed to provide insight into real-time measurements of HCHO emissions from modern vehicles, and WHVC testing formed an essential part of the experimental tests conducted about this issue.

The efficiency of a vehicle's powertrain, relevant to the evolution of transport and plans to eliminate internal combustion engines, is a multidimensional issue. It involves both the design of the engine and its dynamic operation under changing road conditions. Modern internal combustion engines achieve high efficiency through advanced technologies such as high-pressure fuel injection system, turbocharging, and emission control systems. However, in reality, this efficiency is subject to fluctuations due to varying engine loads caused by vehicle traffic and road load.

A key factor affecting powertrain efficiency is driving technique and traffic conditions such as hill resistance and inertia. It is therefore necessary to take these variables into account when assessing fuel consumption and average driveline efficiency. The use of driving cycles, such as SORT or WHVC, allows repetitive testing under road conditions, which is important for evaluating exhaust emissions and testing the efficiency of internal combustion engines under different operating conditions. It is worth noting that, despite plans to phase out internal combustion engines, research into their efficiency and emissions is still being conducted to optimize today and future vehicles.

According to the Diesel Forum website, as of December 2022, 77% of all public transport buses in operation were powered by a diesel engine. Of these, 51% are the latest generation of advanced diesel engine technology that achieves near-low emissions of greenhouse gases, particulates, and nitrogen oxides compared to previous generation buses.

Therefore, the aim of the present study was to test the overall efficiency of a city bus's powertrain, taking into account the combustion engine, transmission, torque converter, and tyre friction on the rollers.

## 2. Scope of study

The research involved performing a driving test on a chassis dynamometer. The test chosen was the World Harmonised Vehicle Cycle. The WHVC is generally used for emissions and fuel consumption studies of different types of HDVs. It is a dynamometer test based on the data set used to develop the WHTC international harmonised non-stationary cycle. The WHVC test is a cycle used for heavy-duty vehicles (HDV) and is based on an emissions-oriented, engine-harmonised test cycle performed on the WHTC engine dynamometer. It is contained in regulations issued by the European Economic Commission. It is a synthesis of on-road vehicle speeds and consists of three stages: Urban, Rural, and Motorway. It is used during vehicle testing and modelling. Results from the WHVC driving cycle can be used for research purposes to compare individual levels of toxic emissions and fuel consumption.

The duration of the entire WHVC test is 1800 seconds (Fig. 1). The test consists of three stages representing urban, non-urban, and motorway driving:

- Stage I (Urban) – 900 s, 0–900 s – represents urban driving at an average speed of 21.3 km/h with a top speed of 66.2 km/h. This stage includes frequent starting, stopping, and idling.
- Stage II (Rural) – 481 s, 900–1381s – represents off-road driving at an average speed of 43.6 km/h with a top speed of 75.9 km/h.

The average speed of stages I and II is 29 km/h.

- Stage III (Motorway) – 419 s, 1381–1800 s – represents driving on the motorway at an average speed of 76.7 km/h with a top speed of 87.8 km/h.

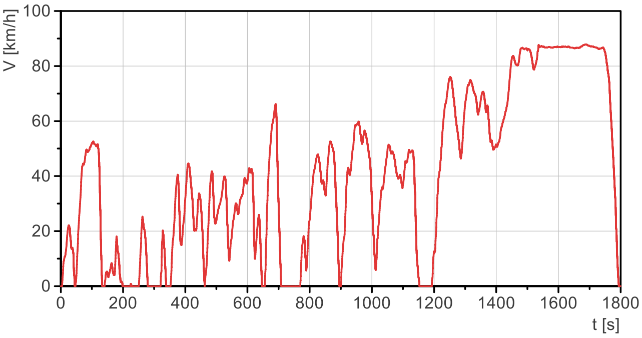

Fig. 1. Vehicle speed profile of the WHVC

During the tests, stages I and II, named Urban and Rural, and part of stage III were carried out. This is due to the fact that stage III of the WHVC driving cycle involves speeds that do not occur during urban bus operation. At the same time, the powertrain control system of the test vehicle limited the maximum speed. The test was carried out in triplicate and the averaged run was analyzed. During the tests, time series were recorded at a frequency of 10 Hz. These were as follows:

- vehicle speed – V [km/h]
- effective wheel power – $P_e$ [kW]
- fuel consumption – $F_c$ [$dm^3/h$]
- accelerator pedal position – APP [%].

The instantaneous vehicle speed value corresponded to the assumed profile with an accuracy of 1.5 km/h. In addition, a regression was developed as a compilation of the speed assumed in the profile and that obtained during the tests. A regression analysis was performed to verify the test. A coefficient of determination of 0.99 indicates correctness.

## 3. Test stand and research object

The tests were carried out on the MAHA LPS 3000 LKW chassis dynamometer. This device allows the simulation, under test bench conditions, of drive train operating conditions similar to those encountered on the road (this applies to both steady and transient states). By realizing the tests, independence from atmospheric conditions and the need for the test vehicle to travel to the control road section was achieved. In addition, the bench conditions increase the possibility of using measuring equipment and ensure the repeatability of test conditions, which is very difficult to achieve under road conditions.

The MAHA LPS 3000 LKW chassis dynamometer was used to simulate road conditions. It is a testing and diagnostic device for vehicles tested under load. The device is intended for trucks and buses with a maximum permissible axle load of 15,000 kg. It is capable of testing heavy vehicles with a power of up to 660 kW. This chassis allows classic performance measurements with a recording of engine mechanical power, torque, engine speed, and wheel speed. The LPS 3000 permits realization driving tests (e.g. NEDC, SORT2, WHVC) to be set up in simulation mode. The recording of additional vehicle operating state parameters is made possible by connecting external devices such as a Diesel MDO 2 toxic gas emission meter or a fuel consumption meter. The basic technical data of the dynamometer is summarised in Table 1.

Table 1. Technical data of the MAHA LPS 3000 LKW chassis dynamometer

| | |
|---|---|
| Axle load | 15,000 kg |
| Roller stand dimensions | 4550 × 1100 × 625 mm |
| Roll length | 900 mm |
| The diameter of the rollers | 318 mm |
| Centre distance of rollers | 565 mm |
| Min. wheel diameter of the vehicle | 400 mm |
| Max. speed | 200 km/h |
| Wheelbase min/max | 820/2620 mm |
| Max. wheel power standard/increased | 300/600 kW |
| Tractive effort standard/increased | 15,000/25,000 N |
| Wheel power measurement error | 2% |
| Measuring system | Strain gauge |
| Electric power supply | 400 V/50 Hz/63 A |
| Total weight | 2350 kg |

The test object was a 12 m-long MAXI-class city bus, a Mercedes Conecto (Fig. 2). Buses in this class are low-floor vehicles with a gross vehicle weight without passengers in the range of 11,000 to 13,000 kg and a length of 10 to 12 m. The total permissible weight including passengers of such a vehicle is 18,000 kg. The passenger capacity of a particular model can vary depending on the interior configuration and version of the bus. In general, it can be assumed that the buses in this family can accommodate between approximately 60 and over 80 passengers, depending on length and seating arrangement.

Fig. 2. Mercedes Conecto LF city bus on a chassis dynamometer

Mercedes Conecto is a two axial, with a rear drive axle. The engine is connected to a four-speed automatic transmission via a torque converter. The vehicle was manufactured in 2009. The bus had a power unit with the designation OM 926 LA. It is an in-line, 6-cylinder, compression-ignition engine with a displacement of 7.23 dm$^3$. It produces a maximum output of 205 kW (278 HP). Average fuel consumption is 39 dm$^3$ per 100 km. The emission standard the vehicle meets is Euro IV.

The data recording system is based on National Instruments hardware and software. The NI cRIO-9024 real-time controller was used, along with the required measurement cards. This included the NI 9862 CAN card, which allows the recording of operating parameters available in the bus diagnostic system. Fuel consumption measurement was based on the communication protocol of the Profibus network available in onboard diagnostic defined by the DIN 19245 was used to measure data. The use of the FMS transmission standard made it additionally to record: vehicle speed, engine crankshaft speed, and accelerator lever position.

The temperature of the drive axle tires and the engine temperature were kept stable during the tests. For this purpose, two blowers set up on two sides of the bus were used. An external source of compressed air for the brake system was also used. This made it possible to eliminate interference from the compressor, which is driven by the engine.

## 4. Results

Figure 3 shows the test results obtained during the WHVC test on a chassis dynamometer. These are in turn: power, accelerator pedal position, fuel consumption, engine speed, and vehicle speed. The results are described detailed in detail in the paper [6].

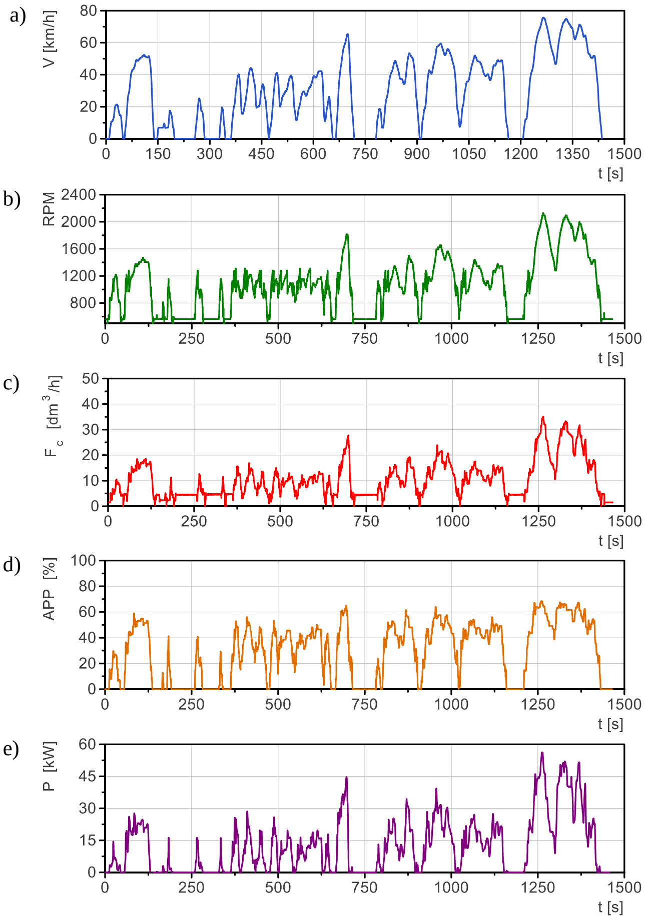

Fig. 3. Time courses of measured values: a) vehicle speed, b) engine speed, c) fuel consumption, d) accelerator pedal position, e) wheel power [6]

The mechanical power generated ranged from –5 to 55 kW. Values below zero occurred during engine braking, with fuel consumption equal to 0. The cycle stages named Urban and Rural were characterized by maximum powers of 40 kW. The Motorway stage was a maximum of 68 kW. Fuel consumption in the first and second stages did not exceed 30 $dm^3$/h. During the Motorway, it increased to 35 $dm^3$/h. Changes in the position of the accelerator lever ranged from 0 to 70%. Engine speed peaked during the last phase of the cycle at around 2100 rpm. Acceleration position pedal signal obtained a maximum value of around 60%

The recorded vehicle speed during the test was compared with the speed given as a reference. The mapping of the obtained speed against the theoretical one was verified by performing regression analysis. The obtained values of the coefficient of determination of 0.97 and the directional coefficient of the straight line of 1.01 are within acceptable ranges.

## 5. Data analysis

The first step in the analysis was to calculate instantaneous efficiency values. This was done using the recorded time waveforms. Referring to the purpose of this study, the analysis determined the efficiency of converting the power contained in the fuel supplied to the engine into mechanical power obtained at the wheels of the bus – Eq. (1). It should be mentioned that the calculated efficiency is only the power conversion efficiency and refers to operating states in which there is a transfer of effective power to the wheels of the vehicle. In road traffic, the phenomena associated with the accumulation of energy in the mass of the vehicle must also be taken into account. This is required for a complete energy balance of vehicle motion. However, in this case, based on the results obtained on a chassis dynamometer, the conversion efficiency of the power flowing from the fuel to the wheels was analyzed.

$$\eta = \frac{P_e}{P_f} \tag{1}$$

The power contained in the fuel was calculated using eq. 2, taking into account the density of the fuel $\rho = 0.82$ $kg/dm^3$ and heating value $W_o = 42$ MJ/kg = 11.94 kWh/kg.

$$P_f = F_c \cdot \rho \cdot W_o \tag{2}$$

The time series of fuel power is presented in Fig. 4. The fuel power delivered is dependent on the speed defined by the WHVC cycle. Speed influences the resistance to motion and the power required to overcome it. The lowest values were found in the past phase of the cycle. Fuel power was a maximum of 170 kW. In the second phase, it increased to 260 kW. By contrast, in the third phase of the driving cycle, where the highest vehicle speeds occurred, wheel power reached a maximum of 360 kW.

Figure 5 shows the time course of the power conversion efficiency of the city bus propulsion system. Due to the method of analysis adopted, which relates wheel power to fuel power, an efficiency of zero was obtained for zero vehicle speed and engine idling. The efficiency value varied from 0 to a maximum of 25%. It can be seen that any starting process is associated with the lowest values of efficiency, which increases with speed. Such low efficiency values may be due to slippage occurring in the torque converter. Above 10 km/h, efficiency varies between 5 and 25%.

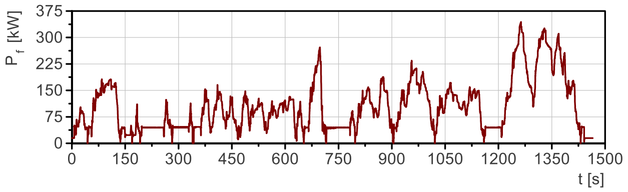

Fig. 4. Time course of measured fuel power

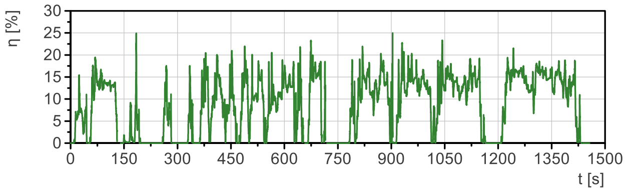

Fig. 5. Time course of the measured power conversion efficiencies in the drive system

Figure 6 provides a comprehensive depiction of the intricate relationship between power conversion efficiency and vehicle speed. The data unequivocally reveals a discernible augmentation in efficiency with escalating vehicular velocity. This empirical observation substantiates the presence of a dynamic state during vehicular acceleration, prominently manifesting within the speed spectrum ranging from 0 to 40 km/h. Within this range, the efficiency experiences a conspicuous flux, underscoring the complex of forces and energy conversion involved during vehicle powertrain system. Beyond this threshold of 40 km/h, the efficiency stabilizes, oscillating within a relatively consistent range of 10–20%. Those phenomenon, underscores the critical significance of optimizing vehicular dynamics for enhanced energy efficiency.

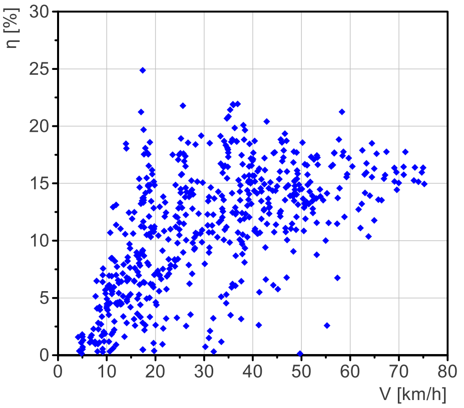

Fig. 6. Power conversion efficiency as a function of vehicle speed

A similar relationship can be seen by analysing Fig. 7, showing the dependence of the efficiency of the power conversion on the power at the wheels. Again, the lowest values were obtained in the range from 0 to about 30 kW. There is a range that corresponds to the acceleration and deceleration of the vehicle. At the same time, this could also be the result of slippage occurring on the torque converter. This may indicate that dynamic states are characterised by lower efficiency. This occurs during the acceleration of the vehicle due to the fact that the efficiency of the individual components of the system is lower than the static characteristics of the individual components. Above 30 kW of power measured at the wheels, the efficiency ranges from 15 to 20%. The range of variation is much smaller as it relates to higher speeds, which can also be inferred from Fig. 6.

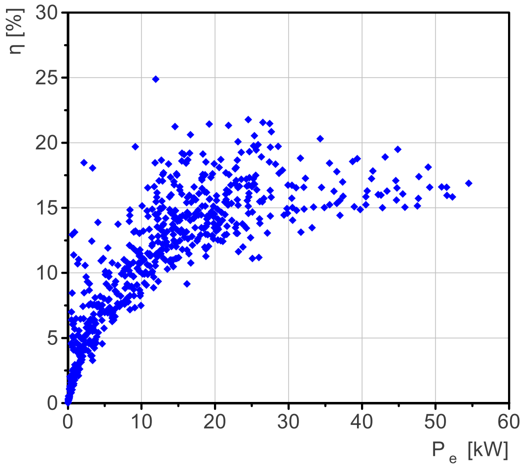

Fig. 7. Wheel power conversion efficiency shown as a function of wheel power

The average value of the conversion efficiency of fuel power to effective power at the wheels of the vehicle was 11.26% (Fig. 8). Figure 8 shows the calculated incidence of efficiency as a function of efficiency and power generated at the wheels of the bus. Three peak values can be observed. The first peak value is for efficiency values of 0–3% with the lowest power at the wheels. The second peak value frequencies around 5% are for efficiencies of around 1% and powers of 10–20 kW. In the context of the analysis presented, the third peak, constituting approximately 3% of the total dataset, manifests as a significant property. This specific peak is concomitant with power output levels of around 30 kW, concurrently yielding an efficiency of the drive train equal to 15%.

Figure 8 accentuates a dependence between efficiency and the power generated by the vehicle's wheels. A conspicuous trend is observed, wherein efficiency ascends up to the 30 kW power, subsequently maintaining a plateau-like constancy within the range of approximately 30 kW to 55 kW. It presents a characteristic of the drive train system under scrutiny.

As a conclusion of the results analysis, it should be noted that, due to the tests carried out on the chassis dynamometer, the calculated efficiencies concerned only the operating states in which power flowed from the engine to the wheels of the vehicle. Real-world road traffic also requires the phenomena of energy storage in the vehicle mass to be considered for a full energy analysis of the movement. However, the analysis based on the results from the chassis dynamometer focused on the efficiency of power conversion from the fuel to the vehicle wheels.

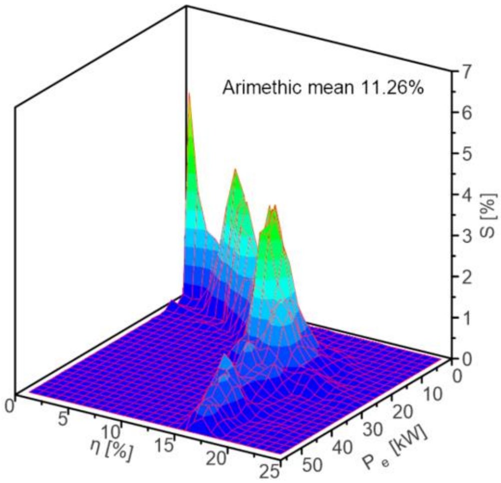

Fig. 8. Incidence of efficiency as a function of efficiency and power generated at the wheels of the bus

The power conversion efficiency of the city bus powertrain varied from 0% to 25%, depending on the vehicle speed. The results showed that the acceleration processes had a lower efficiency, which increased with increasing vehicle speed. This phenomenon could be related to slippage in the torque converter. Above 10 km/h, efficiency remained in the range of 5% to 25%. The analysis showed that efficiency increased with increasing vehicle speed and power at the wheels.

## 6. Summary

The work carried out on the analysis of the energy conversion process in the powertrain of a city bus showed that:

– the tests carried out on the chassis dynamometer do not fully take into account the energy storage in the vehicle mass
– the average overall efficiency was about 11%
– the efficiency achieved varied with the vehicle load, i.e. the vehicle speed achieved
– as the load increased, the efficiency increased, reaching a maximum of approximately 22%.

In conclusion, it should be noted that more than 80% primary energy of diesel fuel could be dissipated in the powertrain of city buses.

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## Nomenclature

| | |
|---|---|
| APP | accelerator pedal position |
| $F_c$ | fuel consumption |
| HCHO | formaldehyde |
| HDV | heavy-duty vehicles |
| $P_f$ | fuel power |
| $P_e$ | effective power |

| | | | |
|---|---|---|---|
| SORT | Standardised On-Road Tests cycles | $W_o$ | fuel heat value |
| V | velocity | $\rho$ | fuel density |
| WHVC | World Harmonised Vehicle Cycle | $\eta$ | efficiency |

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Łukasz Grabowski, DSc., DEng. – Faculty of Mechanical Engineering at the Lublin University of Technology, Poland.

e-mail: *l.grabowski@pollub.pl*

Prof. Mirosław Wendeker, DSc., DEng. – Faculty of Mechanical Engineering at the Lublin University of Technology, Poland.

e-mail: *m.wendeker@pollub.pl*