Method of determining the locomotive engine specific fuel consumption based on its operating conditions

Cite as: AIP Conference Proceedings **2078**, 020053 (2019); https://doi.org/10.1063/1.5092056
Published Online: 04 March 2019

Lukasz Rymaniak, Pawel Daszkiewicz, Jerzy Merkisz, and Yaroslav V. Bolzhelarskyi

Method of determining the locomotive engine specific fuel consumption based on its operating conditions

Lukasz Rymaniak[1, a)], Pawel Daszkiewicz[2, b)], Jerzy Merkisz[1, c)] and Yaroslav V. Bolzhelarskyi[3, d)]

[1]*Poznan University of Technology, Institute of Combustion Engines and Transport, Piotrowo Street 3, 60-965 Poznan, Poland.*
[2]*Rail Vehicles Institute "TABOR", Warszawska Street 181, 61-055 Poznan, Poland.*
[3]*Department of rolling stock and track Lviv branch of Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan, I. Blazhkevych Street 12a, 79052, Lviv, Ukraine.*

[a)]Corresponding author: lukasz.rymaniak@put.poznan.pl
[b)]p.daszkiewicz@tabor.com.pl
[c)]jerzy.merkisz@put.poznan.pl
[d)]jarik762145@gmail.com

Abstract. The paper presents considerations regarding the process of determining the fuel consumption from diesel locomotive engines. In order to know the actual fuel consumption for a given engine, depending on the parameters of the drive system operation, it is necessary to carry out activities aimed at determining its operational indicators. This can be achieved by performing tests in real driving conditions or calculating fuel consumption using a calculation method based on the engine operating conditions. The paper presents the fuel consumption of a Stage II approved locomotive engine, which is used to drive various types of off-road machines and rail vehicles. The presented results of fuel consumption include the values determined on the resistor at set operating points and in real operating conditions. Using the assumptions of the vehicle's operating time density characteristics, a computational method for assessing the fuel consumption of traction locomotives was developed. When comparing the results of bench and real measurements, the influence of the work parameters variability on fuel consumption was determined. In the summary, conclusions regarding the developed method were formulated, and reference was made to the possibility of using this tool to assess the ecological indicators of rail vehicles.

INTRODUCTION

The manufacturers of rail vehicles equipped with internal combustion engines are continuously working to reduce the negative environmental impact of their products as well as to reduce their fuel consumption. This is due to the increasing public environmental awareness, as well as legislative guidelines that are variously defined in the countries or communities concerned. Reducing fuel consumption also has its economic justification, because it reduces transport costs [1, 2]. Therefore, in relation to combustion engines produced even ten years ago, emission factors and fuel consumption have decreased by at least a dozen percent, which contributes to greater environmental protection and is in line with the adopted policy of sustainable development [3, 4]. Railway vehicle internal combustion engines, in the aspect of pollutant emissions, are type approved only at a stationary dynamometer stations. Based on the work carried out in recent years, it should be stated that qualitative and quantitative measurements of exhaust gases and fuel consumption from combustion engines performed in laboratory conditions may significantly differ from the operational results of a given category vehicle, including rail vehicles [5–7].

The development and miniaturization of exhaust measuring equipment in recent years, namely devices in the PEMS mobile exhaust analyzer (Portable Emission Measurement System) group, allows performing more and more thorough environmental testing of vehicles in real operating conditions [8–10]. In the article by Daszkiewicz,

Computational Technologies in Engineering (TKI'2018)
AIP Conf. Proc. 2078, 020053-1–020053-8; https://doi.org/10.1063/1.5092056
Published by AIP Publishing. 978-0-7354-1806-6/$30.00

Andrzejewski, the authors carried out the analyzes were conducted to determine the operating conditions and energy consumption of the SM42 locomotive used during the modernization works on the railway line. As a result of the proposed organizational actions, the share of inefficient engine idle time was reduced by almost 9%, resulting in a reduction in fuel consumption of 8 dm^3, and were demonstrated the differences in measurements between the homologation method and the tests in real conditions. Especially it is useful in relation to rail and track vehicles. At the same time, the application possibilities of these devices are increased. As a result it has become possible to consider the specificity of rail traffic – including maintaining the dimensions of the vehicle even with the installed equipment in the railway gauge limits. The presented work discusses the method of determining the fuel consumption of a traction locomotive engine based on its operating conditions during bench tests and in real operating conditions using PEMS type equipment.

OPERATING CONDITIONS OF COMBUSTION ENGINES USED IN TRACTION LOCOMOTIVE DRIVES

Medium-speed internal combustion engines used in the drive systems of line and shunting locomotives are operated in a range of load characteristics. Their operating parameters variability intervals include changes in the torque and crankshaft rotational speed. The change of the crankshaft rotational speed occurs during starting and stopping of the engine and in transition between individual engine load states – the change of the receiver energy demand is performed by changing the throttle position.

The engine's operating parameters change based on the vehicle drive settings adjusted by the driver. In the research objects used, it was possible to obtain eight throttle positions as well as idle (notch 0). The tested shunting locomotives are operated mainly on notch settings in the range of –4 when working under load. Higher settings are used for quick travel or performing work on the tracks. Based on the authors' research, it was determined that during shunting work notch changes can occur more than 400 times per hour, while when travelling, the number of notch changes usually does not exceed 20 changes total. It should be noted that notch changes have a significant impact on the achieved fuel consumption and the emission of toxic exhaust compounds, which results from the transient operating conditions of the internal combustion engine. The efficiency of internal combustion engines and traction generators varies depending on the load mode or the coil temperature. All functional systems (auxiliary machines) should also be taken into consideration. The total power of auxiliary machines in low notch positions is comparable in size with the power generated at the terminals of the main generator. In technical literature, as a rule, no data is provided on the energy requirements of the auxiliary systems and power losses in the transmission at low notch settings. At the same time, some powers of auxiliary devices (such as compressors, fans) significantly depend on the technical condition of these units, operating conditions, etc.

RESEARCH METHODOLOGY

The tested vehicle was a diesel locomotive pulling heavy loads mainly in coal mines. The drive was powered by a V12 compression ignition engine. The engine had a rated power of 590 kW and the displacement volume was 47.5 dm^3. The drive system met the Stage 2 type approval standard. The adopted research schedule included an original method of harmful compounds emissions measurements in stationary conditions (on the resistor) and in real operating conditions with an additional load. Based on the determined ecological indicators, the specific fuel consumption was assessed.

Exhaust toxicity – the concentration of individual components in the exhaust gases was determined using a device for mass concentration measurement of toxic compounds – the Micro PEMS Axion R/S+ mobile analyzer (Table 1). This device is used to measure exhaust emissions of: hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x) and particulate matter (PM). The concentration of HC, CO, CO_2 is measured using an infrared non-dispersive analyzer – NDIR (nondispersive infrared sensor). Electrochemical analyzers were used to determine the NO and O_2 emission. In the measurement of PM, a method based on Laser Scatter was used. The measuring device is equipped with a meteorological station, a GPS and a module connecting with the on-board vehicle diagnostic system. All measured data were recorded at a frequency of 1 Hz [11].

Tests at determined engine operating points were performed at a test bench, where the engine was coupled with a water resistor, which gave the possibility of applying drive system load. This allows simulating all operating modes that occur during real operation, only neglecting the movement resistance. The resistor used in the tests was filled with a brine solution, where two electrodes were immersed, with a maximum continuous power of 2000 kW.

TABLE 1. Axion R/S+ technical parameters [11]

Gas	Mesaurement Range	Accuracy	Resolution	Type of Mesaurement
HC	0–4000 ppm	± 8 ppm abs. or ±3% rel.	1 ppm	NDIR
CO	0–10%	± 0.02% abs. or ±3% rel.	0.001 vol. %	NDIR
CO_2	0–16%	± 0.3% abs. or ±4% rel.	0.01 vol. %	NDIR
NO	0–4000 ppm	± 25 ppm abs. or ±3% rel.	1 ppm	E-chem
O_2	0–25%	± 0.1% ppm abs. or ±3% rel.	0.01 vol. %	E-chem
PM	0–300 mg/m^3	± 2%	0.01 mg/m3	Laser Scatter

By regulating the separation distance between the electrodes and the active surface of the plates immersed in the electrolyte, the resistance value was controlled and the received energy was converted into heat. Notch positions were used, as measuring points as they can be used to control locomotive operation from the control panel (8 notches + neutral). Subsequently, tests were carried out in real operating conditions. The locomotive was loaded with a weight of 75 000 kg. Measurements were performed on a stretch of track 6.1 km in length, where the total work generated by the drive system was 120 KWh. The average travel speed during the measurement was 8.3 km/h, while the highest recorded speed was 36 km/h. The maximum slope of the route during the tests was 5.6%, and the average for the whole route was 1.3%.

METHOD FOR DETERMINING THE OPERATING TIME DENSITY CHARACTERISTICS AND FUEL CONSUMPTION

Time density (TD) characteristics are used in the construction and optimization works of combustion engines and entire drive systems, and even vehicles themselves. Their use makes it possible to mathematically determine the share of the internal combustion engine operating time and fuel consumption in relation to the engine parameters (crankshaft speed and engine load range) for tests in a given measurement cycle. The operating conditions of locomotives are to a certain extent reproducible due to the fact that these vehicles are traveling on the same routes, according to a specified timetable. Therefore, taking into account the operating time, it is possible to characterize the motion by using a discrete function with coordinates n (crankshaft speed) and T (torque) (Fig. 1). For this purpose, it is necessary to register two synchronous characteristics during the measuring cycle, e.g. using on-board diagnostics of the vehicle/drive unit. For the internal combustion engine operating points occurring during the measurement cycle, a set of different types of data for the n-T coordinates can be determined. This relates mostly to the exhaust emission intensity (expressed in different units), fuel consumption or selected notch settings. On this basis, it is possible to determine the total fuel consumption and ecological indicators for a specific test or measurement cycle.

Producing the time density characteristics requires dividing the work area according to the equation:

$$\Delta \mathrm{n} = \frac{n_{\max} - n_{\min}}{N_i} \tag{1}$$

$$\Delta \mathrm{T} = \frac{T_{\max} - T_{\min}}{T_j} \tag{2}$$

where: N_i and T_j – number of intervals in the operating parameters range of the internal combustion engine.

Additionally the two following conditions must be met:

$$\sum_{k=1}^{N} \sum_{p=1}^{T} t_{(k,p)} = t_c \tag{3}$$

$$\sum_{k=1}^{N} \sum_{p=1}^{T} TD_{(k,p)} = 1 \tag{4}$$

where: N – the range of crankshaft rotational speeds, T – torque range, k and p – operating points in a given second, t_c – cycle duration time.

The time density characteristic contains the relationship between the engine parameters and its operating parameters, which is random. The probability (P) of the occurrence of n and T parameters in the ΔL_s interval is described by:

$$f = P\{(n,T) \in \Delta L_s\} = \iint_{L_s} f(n,T)\,\mathrm{d}n\,\mathrm{d}T \quad (5)$$

In the ΔL_s interval the characteristic value is its midpoint, defined in the article by the arithmetic mean of the beginning and end of speed and torque intervals.

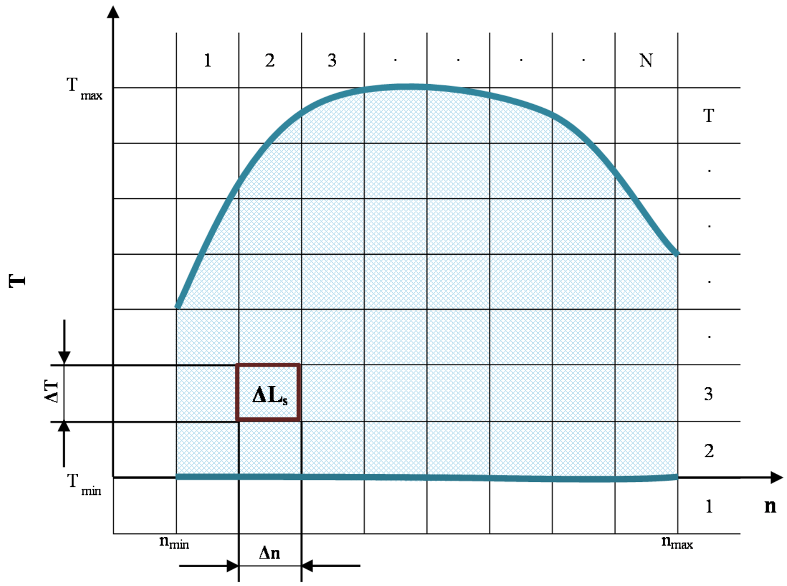

FIGURE 1. Internal combustion engine operating area division; ΔL_s – the base operating interval [12]

A supplement to the considerations carried out is the assessment of the fuel consumption of the tested vehicles in the performed tests. In order to determine specific values the carbon balance method was used, based on the results of road emissions of harmful exhaust components. This allows to accurately calculate the volume of fuel consumed expressed as a function of distance. It is also possible to use data from the on-board diagnostic system or by measuring the change in fuel volume, however, these solutions are subject to certain errors. The carbon balance method for diesel vehicles uses the calculation formula in the following form:

$$FC = \frac{0.1155}{\rho_{fuel}} \cdot [(0.866 \cdot THC) + (0.429 \cdot CO) + (0.273 \cdot CO_2)] \quad (6)$$

where: FC – fuel consumption in [dm^3/100 km], THC, CO, CO_2 – road emission of harmful compounds [g/km], ρ_{fuel} – fuel density at 15°C [g/cm^3].

The specific fuel consumption was the calculated fuel consumption mass divided by the power produced by the internal combustion engine. Data concerning the engine operating parameters came from the on-board diagnostic system. The mass fuel consumption was determined from the carbon balance calculation method (4) modified in accordance with [13, 14]. The article [15] presents considerations regarding determining the NO_x emissions from auxiliary compression-ignition marine engines. It was shown that in order to determine the real impact of a given object on air pollution, it is necessary to first carry out research aimed at determining its emission characteristics. Thus, it is necessary to conduct tests in real operating conditions or to calculate the ecological indicators based on the operating conditions. It was proved that the presented methodology of activities can be used to assess the ecological indicators of vehicles equipped with an internal combustion engine. The article is supplemented with theoretical considerations regarding the problem of pollutant emissions from internal combustion engines.

LOCOMOTIVE FUEL CONSUMPTION FOR STATIONARY TESTS AND IN REAL OPERATING CONDITIONS

When developing the operating time density characteristics, the specificity of traction motors design and the values of their rated parameters were taken into account. Its assumptions were also used to determine the characteristics of specific fuel consumption as a function of the drive system performance parameters. During bench tests, the combustion engine obtained specific operating parameters (rotational speed – power) forced by the given setting. The measurement at each operating point lasted 180 s, where both the emission of harmful compounds and the mass flow of exhaust gases were measured. Using this data, the specific fuel consumption was calculated for notch settings 1–8 (Fig. 2). For idle operation (notch 0) no specific fuel consumption was presented, because the result tended towards infinity. Due to the obtained fixed work points (with variations of less than 2%), the power and crankshaft rotational speed values are presented on the characteristic curve. The obtained results indicate that, the increase of notch value, and thus the increase of engine power, lead to the reduction of the calculated specific fuel consumption values. This means that in subsequent cycles the overall efficiency of the engine's operation increased. For a power of 20 kW at 600 rpm, the specific fuel consumption was 840.9 g/kWh. The most favorable result of 240.1 g/kWh was obtained for the maximum power of 590 kW obtained in tests at 1300 rpm. The average specific fuel consumption value for the entire test was 429.4 g/kWh.

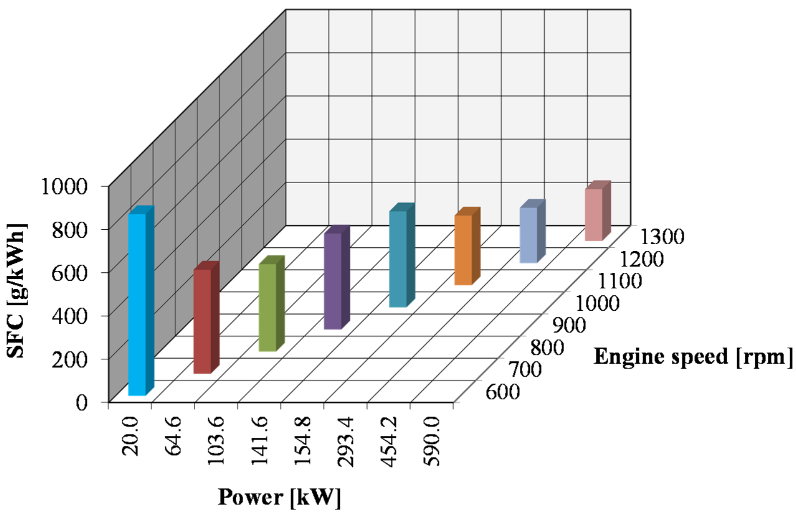

FIGURE 2. Specific fuel consumption results for stationary tests on a resistor

For tests in real operating conditions, the instantaneous parameters of the combustion engine's operation were recorded. On this basis, the operating time density characteristic of the drive unit as a function of the power generated and the rotational speed of the crankshaft were determined (Fig. 3). Parameters of half-closed intervals have been determined for engine operating parameters, excluding the smallest ranges where closed intervals have been applied. This was done in accordance with the previously presented assumptions for the determination of ΔLs. The omission of intervals and using specific values of engine operation parameters instead, as it was done in the characteristics describing stationary tests, would result in the generation of a grid with a very high data point density. This would result in the data presenting the relation studied becoming unreadable.

The presented relation shows that the largest operating time density of 34% occurred in the power interval of up to 100 kW in the lowest rotational speed interval. For the same rotational speeds but for the next power interval (100 kW, 200 kWh, the determined density was 12%, which was influenced by the vehicle's operating conditions (frequent stops, very slow driving) as well as additional engine load resulting from powering the locomotive's functional and auxiliary systems, mainly when stationary. The rotational speed interval (700 rpm, 900 rpm⟩ in the power interval (100 kW, 200 kW⟩, the following operating time densities were 7.3% and 7.1%. For rated parameters (maximum powers and rotational speeds), the density was 0.1%. In the remaining individual work intervals, the values obtained did not exceed 3.3%.

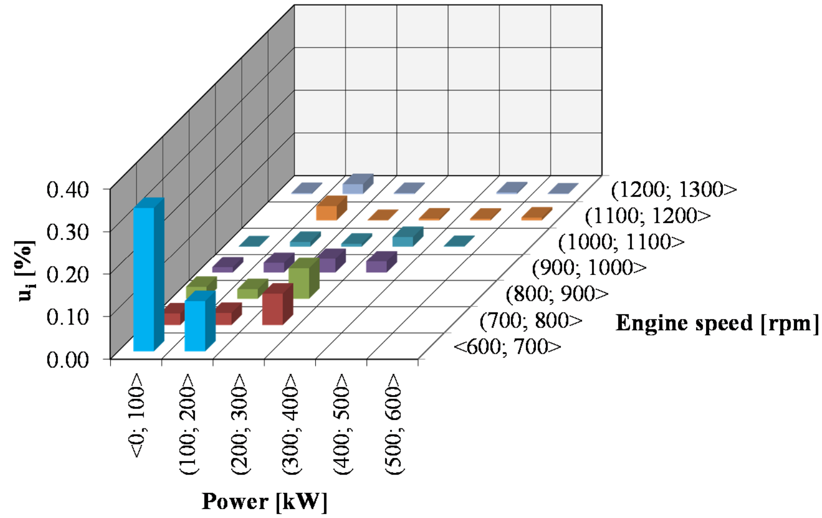

FIGURE 3. The share of engine operating time density during testing of a shunting locomotive in the power – rotational speed range of variability

The specific fuel consumption in real driving conditions was determined based on the harmful compounds emission results, exhaust gas flow and engine operating parameters. The obtained values are presented as a function of power and crankshaft rotational speed (Fig. 4). The highest specific fuel consumption of 826.2 g/kWh was obtained in the highest rotational speeds interval for power values of up to 100 kW. For the same power interval at speeds of up to 700 rpm, fuel consumption of 805 g/kWh was obtained. The characteristics presented show that the specific fuel consumption decreases with increasing power. The smallest value of 311 g/kWh was obtained for the rotational speed interval (1100 rpm; 1200 rpm⟩ in the power interval (500 kW; 600 kW⟩. On the presented characteristics, the results of specific fuel consumption (especially for higher power values) are significantly different from the bench tests. This is because for real operating conditions the analysis was performed for the ΔL_s intervals of engine operation, in which the conditions were dynamic – in terms of rotational speed and load changes. In bench tests the operating conditions were constant and fixed.

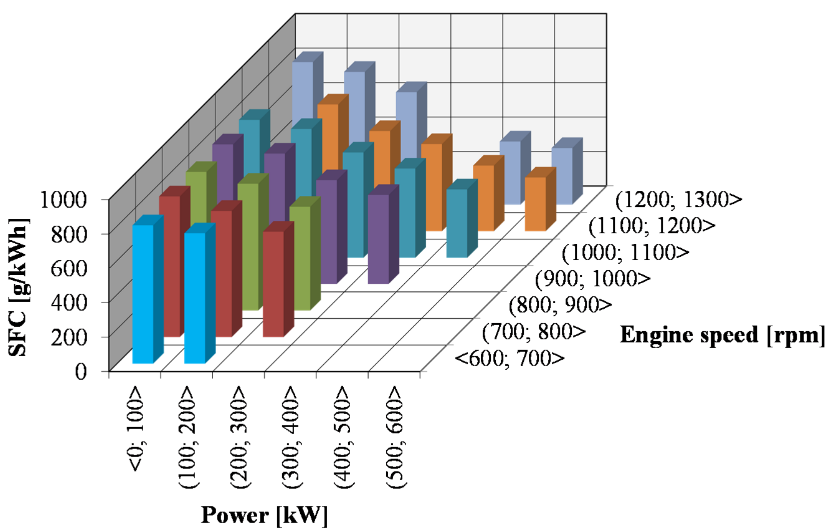

FIGURE 4. The specific fuel consumption determined from the exhaust emission values in real operating conditions

The presented relationships allow to precisely determine the average specific fuel consumption in the SFC_{RDE} measuring cycle. To do this, the following equation is used:

$$SFC_{RDE} = t_c \cdot \sum_{k=1}^{N} \sum_{p=1}^{T} TD_{(k,p)} \cdot SFC_{\Delta Ls} \tag{7}$$

For the performed test the specific fuel consumption was 716 g/kWh. This means that the drivetrain efficiency was low. The obtained results were mainly influenced by a large operating time density in the lowest power and rotational speeds intervals. The established method of obtaining specific fuel consumption can be successfully used for other measuring cycles, where only the drivetrain performance parameters would be registered. The presented tool can be very useful in the optimization of the drivetrain or introduction of changes in the locomotive's operating style by the driver among others. Taking into account the obtained characteristics, it can be stated that the use of a start-stop system would be very beneficial for the efficiency of the vehicle.

SUMMARY

In the field of combustion engine vehicle testing, advanced research work is being carried out. This work concerns mainly the determination of the pollutants emission value and from those results also the fuel consumption in real operation. Due to the specificity of railway vehicle operation and track infrastructure, this type of measurements can be significantly limited and difficult to perform mainly due to the measuring equipment installed on the vehicle exceeding the loading gauge dimensions. As a result it is not always possible to assess ecological indicators during normal operating conditions. Therefore, the appropriate fuel consumption and operating time density characteristics can be used, as shown in the article. To achieve this, the engine's characteristics, operating conditions as well as emission parameters and fuel consumption values determined empirically in bench or track tests should be taken into account.

The determined characteristics of the operating time density confirm that the locomotives of the tested type usually operate in the notch settings of 0–4. This means that high specific fuel consumption values are obtained (due to low overall efficiency), 716 g/kWh was obtained for the test. Referring to the designated characteristics, it can be concluded that the improvement of the vehicle's efficiency can be achieved by using a start-stop system. The presented method of determination of specific fuel consumption may be useful in construction works (e.g. optimization of the propulsion system operation), selection of operational routes or introduction of ecodriving rules for train drivers. The presented method of determining fuel consumption can be successfully used in the assessment of traction locomotives in specific test cycles or actual operating conditions with the option of omitting the registration of selected data. It should be noted, however, that the characteristics should take into account the variability of engine operating parameters in the designated intervals. A comparison of the results of bench and real driving measurements indicates that discrepancies in the obtained values of specific fuel consumption may even amount to 39% (relative to the stationary test conditions).

ACKNOWLEDGMENTS

The study presented in this article was performed within the statutory research (contract No. 05/52/DSMK/0287).

REFERENCES

1. W. Gis, J. Pielecha, J. Waśkiewicz, M. Gis, and M. Menes, "Use of Certain Alternative Fuels in Road Transport in Poland," in *IOP Conference Series: Materials Science and Engineering* **421**, 012040 (2016).
2. B. Pyke, *Global Energy Trends; 2030 to 2050* (Hilbre Consulting Limited. Wirral, 2014).
3. J. Merkisz, L. Rymaniak, Eksploat. Niezawodn. **19**, 522–529 (2017).
4. M. Siedlecki, P. Lijewski, and S. Weymann, "Analysis of tractor particulate emissions in a modified NRSC test after implementing a particulate filter in the exhaust system," in *MATEC Web Conf.* **118**, 28 (2017).
5. P. Fuć, P. Lijewski, M. Siedlecki, B. Sokolnicka, and N. Szymlet, "Analysis of particle mass and number emission from an SI engine with direct fuel injection and a particulate filter," in *IOP Conference Series: Materials Science and Engineering* **421**, 042019 (2018).
6. N. O. Nylund, K. Erkkilä, T. Hartikka, "Fuel Consumption and Exhaust Emissions of Urban Buses," in *VTT Tiedotteita Research Notes*. **2373** (2007).
7. I. Pielecha and W. Cieślik, J. Therm. Anal. Calorim. **126**, 815–827 (2016).

8. P. Daszkiewicz and M. Andrzejewski, "Preliminary analyzes in terms of the possibility of reducing energy consumption by the SM42 locomotive used in track works," in *MATEC Web Conf*. **118**, 00014 (2017).
9. J. Merkisz, J. Pielecha, P. Lijewski, A. Merkisz-Guranowska, and M. Nowak, WIT Trans. Ecol. Envir. **174**, 27–38 (2013).
10. M. Nowak and J. Pielecha, "Comparison of exhaust emission on the basis of Real Driving Emissions measurements and simulations," in *MATEC Web Conf*. **118**, 26 (2017).
11. GLOBALMRV materials.
12. M. Cichy, Silniki Spalinowe **2-3**, 75–77 (1986).
13. P. Fuć, P. Kurczewski, A. Lewandowska, E. Nowak, J. Selech, and A. Ziółkowski, Int. J. Life Cycle Assess. **21**, 10, 1438–1451 (2016).
14. P. Fuc, P. Lijewski, A. Ziolkowski, and M. Dobrzyński, J. Electron. Mater. **46**, 3145–3155 (2017).
15. L. Rymaniak, J. Pielecha, and L. Brzeziński, "Determining the NOx emission from an auxiliary marine engine based on its operating conditions," in *MATEC Web Conf*. **128**, 26 (2017).