Article citation info:
Bednarek M, Ziółkowski A, Jagielski A, Siedlecki M. The analysis of the operating conditions of a heavy-duty engine of a vehicle designated for timber transport in terms of compliance with the RDE procedures. Combustion Engines. 0000;XXX(X):xx-xx. https://doi.org/10.19206/CE-193859

Maciej BEDNAREK
Andrzej ZIÓŁKOWSKI
Aleks JAGIELSKI
Maciej SIEDLECKI

Combustion Engines
Polish Scientific Society of Combustion Engines

The analysis of the operating conditions of a heavy-duty engine of a vehicle designated for timber transport in terms of compliance with the RDE procedures

ARTICLE INFO

Received: 20 August 2024
Revised: 10 September 2024
Accepted: 27 September 2024
Available online: 11 October 2024

According to the data provided by the Polish Central Statistical Office, the years 2000–2020 have seen a general increase in the amount of extracted timber, reaching 43%. The process of obtainment and transport of timber has many stages involving multiple vehicles and machines. The prevailing type of machinery is HDVs (heavy-duty vehicles). Their application is dictated by the fact that high-tonnage-rated vehicles are characterized by the greatest efficiency. The vehicles from this group are homologated under laboratory and actual traffic conditions. It is noteworthy that the transport process of timber takes place under extremely varied conditions – paved urban and rural roads a well as unpaved forest tracks. This renders the mode of operation non-compliant with the conditions set forth in the UE 582/2011 standard. Therefore, the authors decided to carry out an analysis of the operating conditions of a vehicle fitted with an HD engine used in the process of timber transport in terms of its compliance with the RDE (Real Driving Emissions) procedures. The analysis was performed based on investigations carried out under actual traffic conditions with the use of the PEMS equipment. The research object was a tractor-trailer fitted with removable stanchions and a crane used for timber handling. The paper presents, inter alia, the engine operating timeshare characteristics as a function of engine load and speed. The authors also compared the real-world engine operating conditions with the assumptions of the RDE procedures.

Key words: *RDE, PEMS, in-service conformity procedure, HDV*

1. Introduction

Higher traffic congestion, advancement of scientific research on the negative impact of transport related pollution as well as increased sensitivity of the society to health hazards associated with the inhalation of exhaust gases have caused the legislators to continuously introduce legal acts forcing the reduction of the negative environmental impact of the transport sector [19, 4]. The main polluting components of exhaust gas are particulate matter (PM), hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), and carbon dioxide (CO_2) [2]. Multiple research works confirm that these components have a negative impact on human health and the natural environment (the emitted greenhouse gases contribute to the growing greenhouse effect) [12, 36, 40]. Some of the exhaust components, including selected hydrocarbons and particulate matter, are carcinogenic [24, 30].

The pioneer in the emission-reducing legislation is the United States of America. In 1968, the US passed the first legislation on exhaust emissions [38]. In the EU, the first legal standard aiming at a reduction of vehicle exhaust emissions was introduced in 1991. Legislation regarding passenger vehicles (PC) and light-duty vehicles (LDV) evolved throughout the years. More and more chemical components were introduced to the list, and emission limits became more stringent, forming the subsequent Euro 1–Euro 6d standards. This paper discusses vehicles of the GWV (gross vehicle weight) greater than 3500 kg. The standards for this category of vehicles in the EU were introduced a year after such standards had been imposed on PC and LDV vehicles. The standards for heavy-duty vehicles are included in regulations commonly referred to as Euro I–Euro VI. The most recent communications from the EU legislators prompt the introduction of a new Euro 7 standard pertaining to PC, LDV and HDV vehicles [1]. Increasingly stringent emission standards forced the manufacturers to tune their engines and redesign them. The said standards also sparked dynamic technological advancement of aftertreatment systems [15] and, more importantly, dynamic advancement of the alternative powertrain technology. According to the available data, the number of vehicles in the EU fitted with alternative powertrains is growing [6]. In 2022, the European Parliament adopted a resolution that in the European Union, starting in 2035, purchasing a new vehicle fitted with a conventional powertrain would not be possible. Additionally, the European institutions plan that by 2050, all EU member states will become zero-emission ones [7]. It is noteworthy that the market share of passenger vehicles fitted with alternative powertrains – BEV (battery electric vehicle), HEV (hybrid electric vehicle), and PHEV (plug-in hybrid electric vehicle) is still only slightly more than 2% [26]. What is more, these powertrains are widely applied in passenger vehicles only. In the case of HDVs, these powertrains are not as commonplace, even though their technological advancement can only boost the attractiveness of heavy-duty road transport, as has been stressed by the authors in [5].

As the new standards were introduced and the limits of individual exhaust components were changed, the methods of their measurement evolved. HDV vehicles are homologated under laboratory conditions on an engine dynamometer. Pursuant to Regulation 49 of the EEC UN, two research cycles apply – stationary WHSC (World Harmonized Stationary Cycle) and transient WHTC (World Harmonized Transient Cycle). These tests superseded the earlier ESC and ETC ones. The newly designed cycles were made to better reproduce the actual traffic conditions of heavy-duty vehicles [23]. This aimed to obtain the most reliable exhaust emissions measurement results through an accurate reflection of the engine's operating parameters. It is noteworthy that the said research cycles are also used by research institutions to evaluate the engine operating parameters or determine a variety of relations emission-wise. For example, the authors of [34] used the World Harmonized Stationary Cycle to determine the influence of mixtures of n-butanol and diesel oil on the exhaust emissions and performance of a diesel engine. The investigations were carried out for the entire cycle and for its individual portions. An important component of the analysis presented in the said publication was the discussion related to engine torque and power output. In [4], the authors also used the WHTC procedure in their investigations to assess the influence of the HVO fuel on the engine operation and its performance. In this case, however, a modification of the cycle was necessary because, as the authors indicated, the configuration of the test stand for the investigated engine was inappropriate for the transient stages of the procedure. In [20] the WHTC test was used to investigate the particulate matter emission from a spark ignition engine fueled with CNG and LNG. The World Harmonized Stationary and Transient Cycles were also applied to investigate the emission of nitrogen oxides from a diesel engine fitted with an experimental catalytic converter based on the catalyst combination strategy [37]. Lim [14] et al, based on investigations carried out according to WHSC, generally evaluated a spark ignition engine fueled with synthetic natural gas. The authors of [28], following the results obtained in the World Harmonized Transient Cycle, analyzed the influence of the warm-up phase of an HDV vehicle on the emission of nitrogen oxides.

Laboratory tests do not fully reflect the engine operating conditions, hence, their exhaust emissions. This has been confirmed by multiple research works described in [9, 21, 33, 35]. The advancement of measurement technology has led to a point where the most reliable data are obtained in tests performed under actual traffic conditions. According to many authors, it is the best method of measurement of exhaust emissions and engine operating parameters. It enables very accurate and detailed measurement of the exhaust emissions and engine parameters in stationary, dynamic, and transient conditions [10, 11, 42]. These investigations widely incorporate the use of the PEMS equipment (Portable Emissions Measurement System), particularly when testing emissions according to the RDE (Real Driving Emission) procedures [17, 25]. The equipment is also capable of a detailed analysis of the engine operation [2, 29] and is frequently used to investigate the influence of multiple factors on exhaust emissions. Lee, Junhong, et al. [13] used a portable emission measurement system to investigate the exhaust emissions from construction machinery under actual operating conditions. Mądziel [16] used the data from a PEMS system to model the emission of carbon dioxide from a vehicle fueled with LPG. In [8], the authors presented investigations of energy consumption and exhaust emissions from a plug-in hybrid. One of the measuring instruments in this project was portable emission measurement equipment. It is noteworthy that, aside from the measurement of individual exhaust emissions, through a direct connection to the vehicle OBD system, it can also record the engine operating parameters such as engine torque and speed [27]. For example, the authors of [43] used Semtech D.S. for the research of an HDV vehicle. The aim of their work was to analyze the parameters of the engine fitted to the research object. The authors of [32] also analyzed an HDV vehicle engine operating parameters based on tests performed under actual traffic conditions. The aim of their work was to investigate the performance of an LPG-fueled engine upon a modification of the intake system. [18] analyzes the operating parameters of a farm tractor engine during fieldwork. The possibility of performing research in real-world operating conditions allowed a detailed analysis of the operation of the said engines. For example, research presented in [18], revealed the fact that the operating speed of a farm tractor varies narrowly, which results from the nature of its work.

Many of the above-mentioned research works are performed under real-world operating conditions of the investigated objects. As has been emphasized in [15], the researchers have observed that the homologation procedures do not always fully reflect the actual conditions of operation of the tested objects. In this respect, HDV vehicles are a special case as they are operated under extremely varied conditions (both road and non-road). An example of vehicles whose model is not compliant with the conditions set forth in the standard procedure are those operated in mountain areas, on construction sites, on farms, or in timber transport. Therefore, in this paper, the authors undertook to analyze the actual operating conditions of a vehicle used for the carriage of timber and compare it with the RDE requirements.

2. Research methodology

2.1. Research objects

In the performed investigations, the authors used a heavy-duty truck designated for carriage of timber (Fig. 1). It was composed of a tractor unit coupled with a stanchion trailer and a hydraulic trailer crane fitted for timber handling. The vehicle was fitted with a 6-cylinder (353 kW @1900 rpm) diesel engine. The maximum torque of 2300 Nm was produced at 1200–1500 rpm. The engine displacement was 12.419 dm^3.

Fig. 1. Research object

The vehicle was Euro VI compliant, fitted with an aftertreatment system composed of an SCR (selective catalytic reduction), a DPF (diesel particulate filter) and a DOC (diesel oxidation catalyst). The technical specifications of the research object have been presented in Table 1.

Table 1. Specification of research objects

Parameter	Value
Type of engine	Diesel
Engine capacity	12.419 dm^3
Maximum power output	353 kW at 1900 rpm
Maximum torque	2300 Nm at 1050–1400 rpm
Number of cylinders	6 cylinders, straight
Aftertreatment	DOC+DPF, SCR, ASC
Fuel system	Common Rail

2.2. Measuring instruments

For the investigations, the authors utilized Axion RS+, a portable exhaust emission measurement system (Fig. 2a) and TEXA TXT. The first of the devices measures the concentration of individual gaseous exhaust components. The equipment by Global MRV allows the measurement of both gaseous components and particulate matter. Carbon monoxide, carbon dioxide, and hydrocarbons are measured through a non-dispersive infrared method (NDIR – *Nondispersive Infrared Detector*), while nitrogen oxides are analyzed through an electrochemical analyzer. The concentration of particulate matter is measured using the laser scatter method. Axion RS+ can also record the operating parameters of the engine (engine torque and speed). Additionally, the authors used TEXA Navigator TXT (Fig. 2b) whose purpose was to pull the engine operating parameters from the vehicle OBD system.

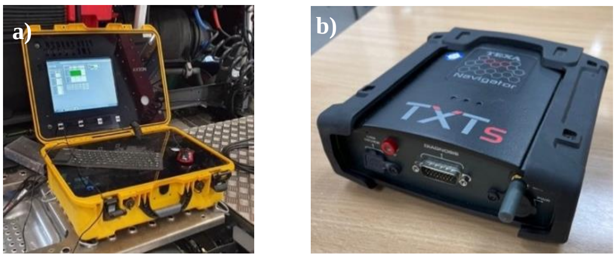

Fig. 2. Axion RS+ (a) and TEXA Navigator TXT (b)

2.3. Research cycle

The tests were carried out under actual conditions of operation of the HDV vehicle. The test procedure was designed to most accurately reproduce the standard process of operation of the research object. The tests were carried out in central Poland. The forests in this region cover ¼ of the area [31]. The test was carried out twice. The first one took place in early autumn. The second took place in more arduous winter conditions. The test reflected the actual model of vehicle operation. This allowed an analysis of the results that pointed to weak spots and non-compliance of the operation model with the homologation conditions for the HDV vehicles. The test routes have been presented in Fig. 4. Each of the research cycles had four stages: a trip to the timber storage with an unloaded truck, timber handling, a trip from the storage facility and unloading. Due to the location of the timber storage area, both the trip to and from the storage facility took place on unpaved forest roads. This is very characteristic of the timber transport process. In the autumn test, the length of the test route was approx. 49 km (paved roads 43.5 km and unpaved roads 5.4. km). The test route in the winter test was a little more than 42 km (paved roads 8.77 km and unpaved roads 33.4 km). The start and end point of the routes was the sawmill.

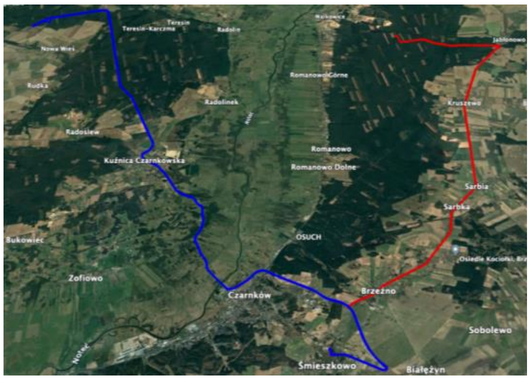

Fig. 3. Test routes

3. Results of the study

3.1. Speed profile and test routes

The vehicle speed profiles (Fig. 4) were composed based on the obtained results. Due to the nature of the research process, this analysis was carried out in two stages depending on the type of test route. The characteristics clearly indicate three stages of the research process (loading, driving on paved roads and driving on unpaved forest roads). Individual portions of the research cycle vary in terms of dynamics and driving speed. In the autumn portion, the vehicle operated at an average speed of 30 km/h. On the forest roads, it drove at an average speed of 9.5 km/h, while on the paved roads, the average speed was 57 km/h. The winter conditions did not dramatically influence the nature of the test drive. On the paved roads, the vehicle drove with an average speed of 51.7 km/h, and on the forest roads – 13.9 km/h.

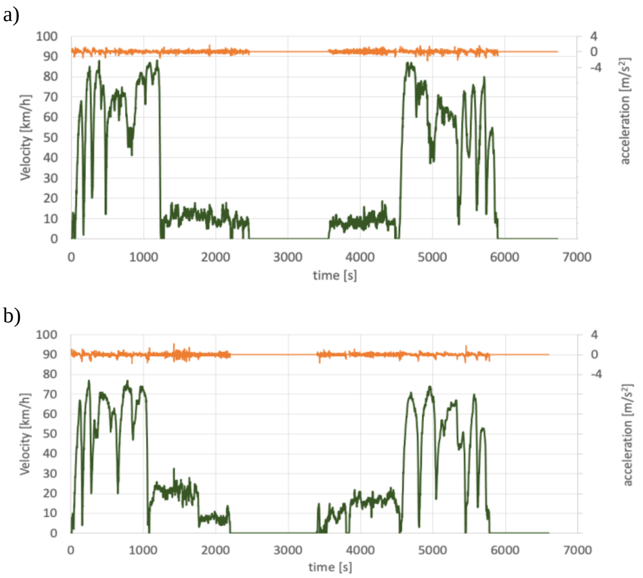

Fig. 4. Speed profiles of the research object: a) the autumn test, b) the winter test

3.2. Operating parameters of the engine

Due to the complexity of the research procedure, the analysis of the HDV's movement parameters in the process of timber transportation will be carried out in sections corresponding to the different stages of the research test, i.e., while driving on paved roads (with and without a load), while driving on unpaved forest roads (also with and without a load), and during loading operations, divided into the autumn and winter test. To present a comprehensive analysis of the performance of the heavy vehicle's drive unit in the process of transporting timber, loading processes were also studied. Because the test vehicle was equipped with a crane, there was no need to engage additional equipment for the loading and unloading of raw timber. During the tests, the vehicle transported approximately 20 tons of timber.

During the tests, instantaneous engine load and speed were recorded. This allowed composing the characteristics of the timeshare of the engine operation in relation to its parameters. The results are presented and discussed below.

The bar graphs have been presented in Fig. 5–7. When comparing the autumn test with the winter one, one may observe that the engine operating areas are similar in individual stages of the test. The tests have shown that, when driving on paved roads, the engine operated in the torque interval of 0–2300 Nm and engine speed interval of 800–1600 rpm for the autumn test and 0–2000 Nm and 800–1600 rpm for the winter test. When driving on the paved roads in the autumn test (Fig. 5a, 5c), a significant share of the speed (1200 rpm; 1600 rpm> and torque (0 Nm; 2400 Nm> intervals were observed. In the winter test, when driving without a load (Fig. 5b), the predominant engine operating area was (0 Nm; 1200 Nm> and (800 rpm; 1800 rpm>. When carrying timber on paved roads in winter conditions (Fig. 5d), the engine operated at the same torque intervals as on the forest roads, but the engine speed interval was 600–1600 rpm. During the winter test, the intervals of the discussed parameters were the same as for the test drives of an empty truck. An increase was observed in the operating timeshare in the (1200 rpm: 1600 rpm> speed interval.

In the second portion of the test covering the forest roads, the engine operated in the same engine speed interval as on the paved roads, but with a much lower load. In the autumn test, during the test drive performed on an empty truck (Fig. 6a), the engine predominantly operated in the load interval of (0 Nm; 800 Nm>. During the winter test (Fig. 6b), the engine predominantly operated in the load interval of (0 Nm; 400 Nm>. In both tests, the transport of timber resulted in an increased engine operation in the torque interval of 400–800 Nm (Fig. 6c and 6d).

The investigations have shown that during timber handling (Fig. 7a–d), the engine operated almost exclusively in the engine speed interval of 800–1200 rpm and torque 0–800 Nm. During the test carried out in the summer-autumn conditions, the load was predominantly 400–800 Nm. During the winter test, a much greater operating timeshare of the engine in the torque interval of 0–400 Nm was recorded.

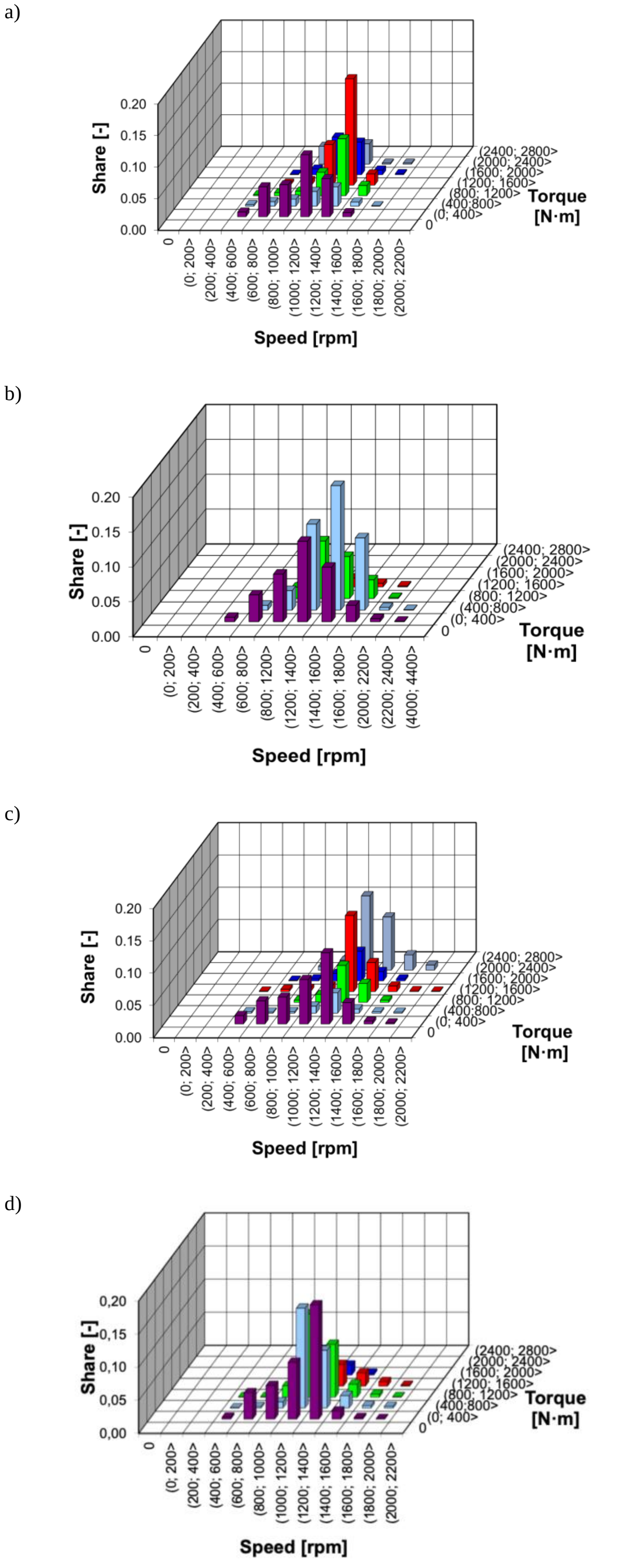

Fig. 5. Engine operating time share as a function of engine torque and speed when driving on paved roads loaded: a) the autumn test, b) the winter test, and loaded c) the autumn test, d) the winter test

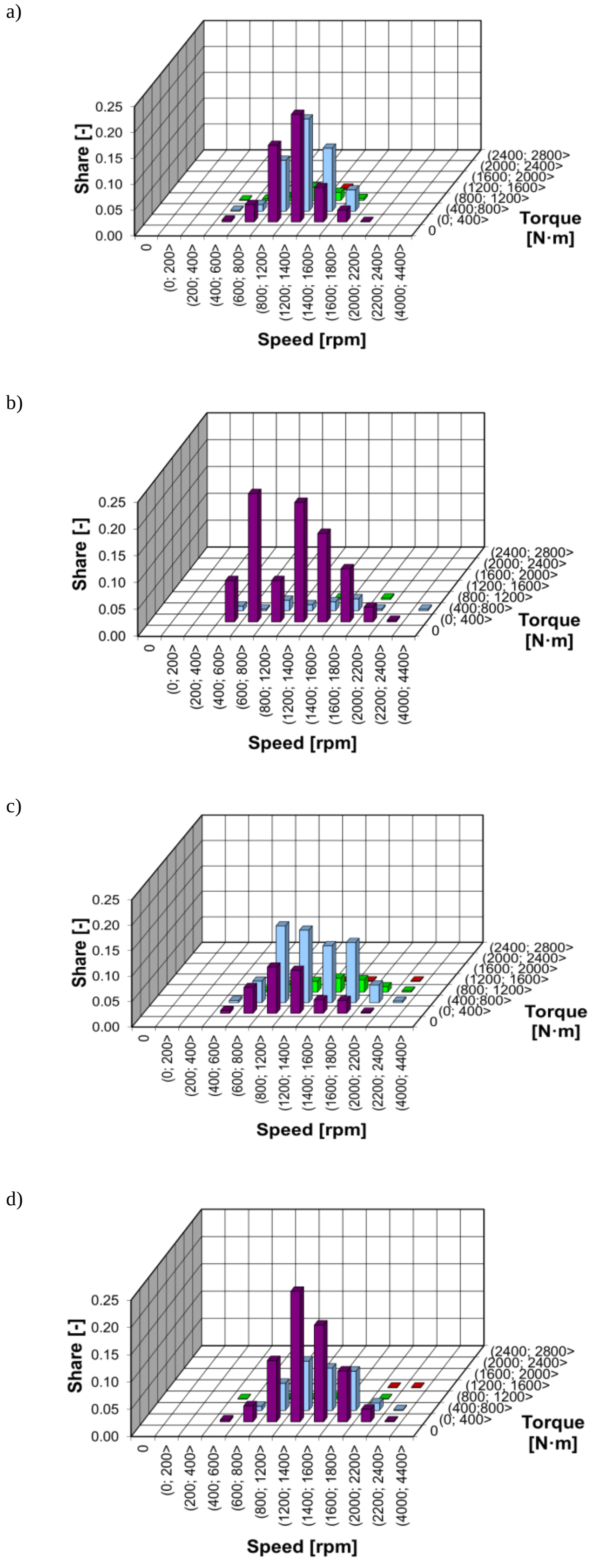

Fig. 6. Engine operating time share as a function of engine torque and speed when driving on unpaved roads (forest) unloaded: a) the autumn test, b) the winter test, and loaded: c) the autumn test, d) the winter test

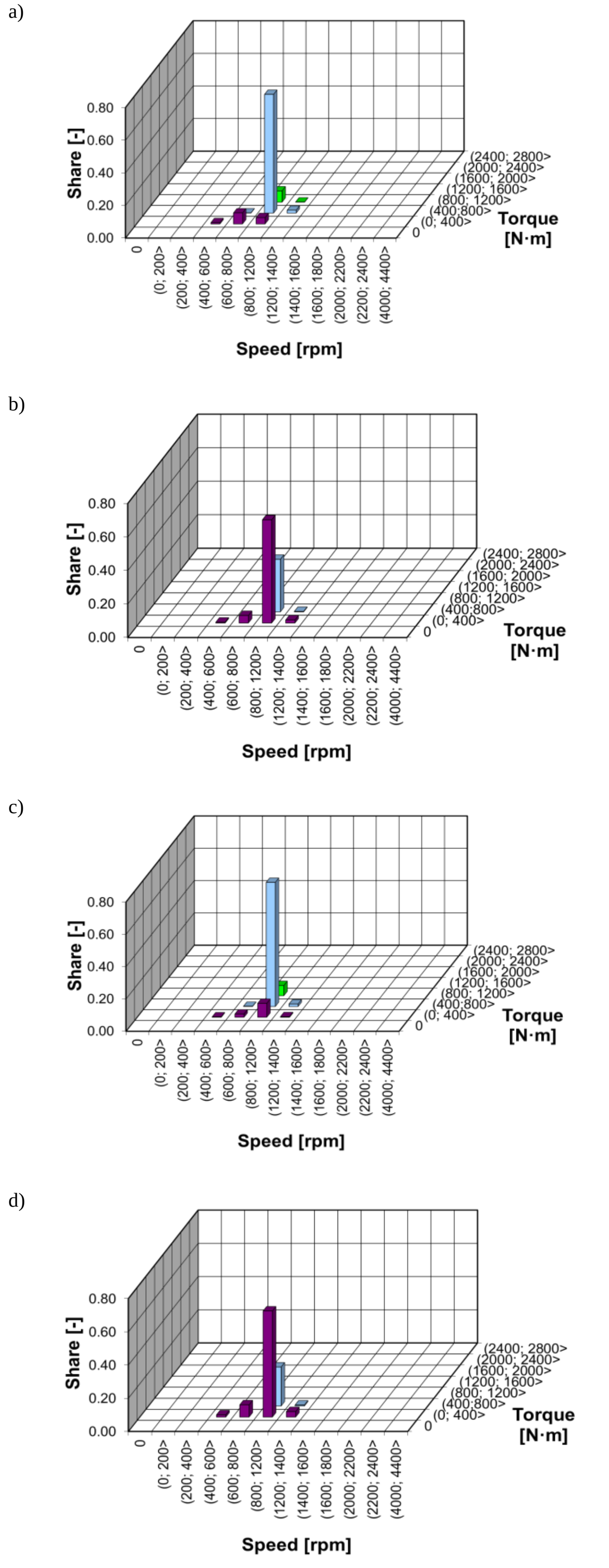

Fig. 7. Engine operating time share as a function of engine torque and speed when loading timber (empty truck): a) the autumn test, b) the winter test, and unloading timber: c) the autumn test, d) the winter test

3.3. Analysis of compliance of the transport cycle with the RDE test procedure

Based on the performed speed profile and engine parameter analysis in both tests, we may confirm that the tests are similar. Therefore, the proposed research cycle is representative of the timber transport process. The research object is subject to standard HDV vehicle homologation procedures. These vehicles or their engines undergo an in-service conformity procedure. precisely defines the procedure of compliance verification, including the conditions of the test drive and operational requirements. Based on the obtained results, the compliance of the homologation procedure with the actual transport cycle was analyzed. The procedure must be composed of three portions whose length (depending on the vehicle category) has been presented in Table 2.

Table 2. Duration of individual test stages in the RDE compliance test

Test portion	M_2 and M_3	N_2	N_3
Urban	45%	45%	20%
Rural	25%	35%	25%
Motorway	30%	30%	55%

Table 3 presents the results of the test drive parameters required by the legislator together with the results obtained during the test performed under actual operating conditions. The obtained values indicate that each of the stages differs from the procedure recommended by the European Commission. It is noteworthy that the procedure does not include the non-road portion, which, in the case of timber carriage, constitutes up to 10–20% of the entire transport cycle. The motorway part of the autumn test constitutes 30% of the transport cycle. In the case of the winter test, this part is a little above 1% of the entire cycle. Such a low value results from the fact that the road conditions render driving at high speeds almost impossible. It is noteworthy that the nature of the process of cutting and extracting timber is dependent on the time of year. For example, timber cut in autumn must be extracted before the vegetation period begins [22, 39]. When analyzing the urban and rural portion of the test, one may observe that the percent values in the real-world test were exceeded compared to the prescribed standard. The exception is the urban portion in the autumn test, in which it was a little above 11% of the entire cycle. This may result from the fact that the test route led through the Czarnków beltway and avoided entering the largest city in the region.

Table 3. Duration of the test drives in individual portions of the test against the requirements of the RDE procedure for heavy-duty vehicles

Test portion	Unpaved roads	City	Rural	Highway
Urban	11%	11.5%	47.2%	30.3%
Rural	20.8%	44%	34%	1.2%
Motorway	–	20%	25%	55%

The regulation also defines the operational requirements. It assumes that the test, as well as the pulling of the data from the OBD system, continues without interruptions. These requirements were fulfilled in both the autumn and the winter tests. The legislation also details the duration of the test. It was described as the time necessary to obtain five times the reference mass of carbon dioxide in kg per cycle from the WHTC test (World Harmonized Transient Cycle) or the time necessary for the tested object to perform five times the work prescribed by the WHTC test procedure. The authors decided to validate the duration of a standard transport cycle in terms of its compliance with the HDV RDE procedure.

The authors calculated the work performed by the engine of the tested object in the WHTC test. Based on the actual torque curve and using a spreadsheet with the appropriate function, the actual torque in Nm was calculated. Based on it, the instantaneous engine power was calculated, which enabled the development of the drive unit's operation in the WHTC test in kWh. The results have been presented in Fig. 8. The obtained results clearly indicate that none of the test drives met this requirement. The work performed by the engine in the autumn test was more than 1.5 times smaller than required, and the one performed in the winter test was almost 2.5 times smaller than required. Based on the previous observations, one may confirm that a standard operational model of the investigated vehicle is non-compliant with the RDE test model.

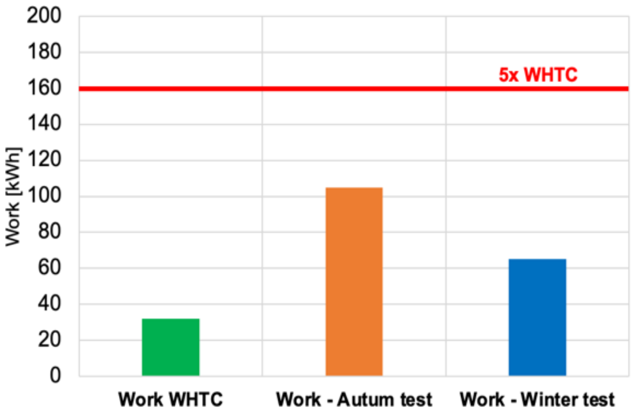

Fig. 8. Work performed by the investigated object in individual tests

The group of vehicles discussed in this article is approved based on procedures that do not consider the impact of unpaved roads on emissions. As confirmed in earlier sections, these roads have a significant impact on the performance of truck power units, which directly affects the number of toxic emissions into the atmosphere. Figure 10 shows a comparison of the emissions of the studied facility. Successively, Fig. 9a shows the results for the test conducted in autumn and Fig. 9b – the results for the winter test. The indicators shown were obtained by comparing the test's gaseous compound emissions with the limits specified in the standard. In both tests, the emission factors did not exceed 1. It is worth noting, however, that they differ significantly from each other. This is due, among other things, to the differences between the two routes – including their length and mainly the difference in the condition of their pavement. These factors significantly affect the operation of the propulsion units, which translates directly into exhaust emissions. Although the values obtained in the test are less than the limit values, it is worth noting that the tests that constitute the actual process of their operation do not meet the requirement of homologation tests, as proven in the earlier parts of this article. Based on the research test it can be considered that the analysis conducted is representative of the national timber transportation system in which HDVs are used. This can be said because each step of the standard timber transportation process was considered in the analysis.

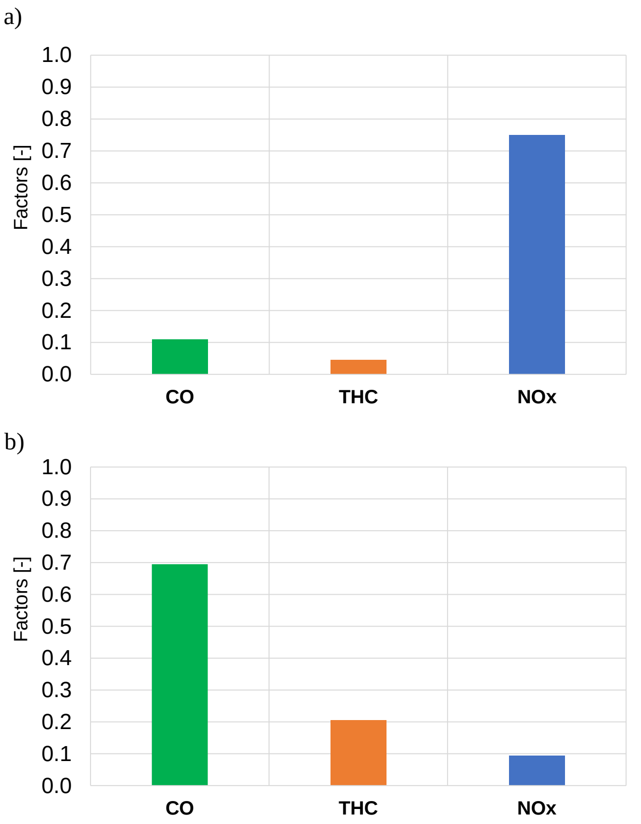

Fig. 9. Compliance factors for exhaust gaseous emissions of tested trucks: a) autumn test, b) winter test

4. Summary

Different climatic conditions, such as low temperatures and rainfall, have a significant impact on truck emissions and fuel consumption. In cold weather, engines take longer to warm up, which increases fuel consumption, especially when starting. In addition, cold weather causes more rolling resistance in tires, which also leads to higher combustion. Rainfall affects the aerodynamics of the vehicle and causes more drag from wheel contact with wet pavement, which further increases fuel consumption. In turn, increased fuel consumption leads to higher emissions, which has a negative impact on the environment. As a result, adverse weather conditions can significantly reduce the energy efficiency of trucks. However, this paper is intended to draw attention to the fact that current approval procedures do not consider the actual operating models of HDVs used in off-highway transportation.

Literature analysis allows a conclusion that heavy-duty vehicles (category N1 in particular) are currently used in the carriage of any type of cargo. The nature of their application can, thus, vary widely. The real-world investigations described in this paper were carried out at different times of the year. Therefore, they varied in terms of road conditions and ambient temperatures. The analysis of the obtained vehicle and engine operating parameters proves that the engines operated in similar intervals irrespective of the ambient conditions. We can, therefore, treat these tests as representative of the discussed timber transport process. The performed research leads to a conclusion that the operational model of heavy-duty vehicles operating under variable conditions does not reflect the model specified in the RDE procedure. The analysis of the engine operating conditions in terms of RDE compliance has shown that the main assumptions as to the test drive conditions and operational requirements are inadequate. Vehicles carrying timber operate on paved as well as unpaved roads (these are not included in the procedure). Individual stages of the RDE test (urban, rural, motorway portions) did not comply during the tests either. Additionally, the test duration criterion was not met (it is noteworthy that the research object was a truck designed to carry timber). Heavy-duty vehicles are used in different transport processes that are also composed of portions involving non-road operation. An example of such could be HDV machinery operating in farm fields, construction sites or open cast mines. Therefore, it is important to further investigate a greater number of research objects and perform detailed analyses of the compliance of their operational model with the legislative assumptions related to RDE testing.

Acknowledgements

The study presented in this article was performed within the statutory research (contract No. 0415/SBAD/0326).

Nomenclature

CO	carbon monoxide
CO_2	carbon dioxide
NO_x	nitrogen oxides
SI	spark ignition
THC	hydrocarbons
RDE	real driving emission
PEMS	portable emission measurement system
ASC	ammonia slip catalyst
DOC	diesel Oxicat
DPF	diesel particular filter
SCR	selective catalytic reduction

Bibliography

[1] AVL List. https://www.avl.com/en (accessed on 06.06. 2023).

[2] Biswal A, Singh V, Malik L, Tiwari G, Ravindra K, Mor S. Spatially resolved hourly traffic emission over megacity

Delhi using advanced traffic flow data. Earth Syst Sci Data. 2023;15;661-680. https://doi.org/10.5194/essd-15-661-2023
[3] Borken-Kleefeld J, Dallmann T. Remote sensing of motor vehicle exhaust emissions. International Council on Clean Transportation. 2018.
[4] Bortel I, Vávra J, Takáts M, Effect of HVO fuel mixtures on emissions and performance of a passenger car size diesel engine. Renew Energ. 2019;140:680-691. https://doi.org/10.1016/j.renene.2019.03.067
[5] Brach J. Konkurencyjność współczesnego ciężarowego transportu samochodowego. Zeszyty Naukowe Uniwersytetu Szczecińskiego Problemy Transportu i Logistyki (in Polish). 2015;319-344. https://doi.org/10.18276/ptl.2015.29-23
[6] European Environment Agency. EEA Report No 2/2022. Decarbonizing road transport — the role of vehicles, fuels and transport demand. https://doi.org/10.2800/68902
[7] European Parliament. https://www.europarl.europa.eu/portal/en (accessed on 6.06. 2023).
[8] Frey HC, Zheng X, Hu J. Variability in measured real-world operational energy use and emission rates of a plug-in hybrid electric vehicle. Energies. 2020;13;1140. https://doi.org/10.3390/en13051140
[9] Giechaskiel B, Clairotte M, Valverde V, Bonnel P. On-road emissions of passenger cars beyond the boundary conditions of the real-driving emissions test. Environ Res. 2019;176: 108572. https://doi.org/10.1016/j.envres.2019.108572
[10] Jaworski A, Mądziel M, Lew K, Campisi T, Woś P, Kuszewski H et al. Evaluation of the effect of chassis dynamometer load setting on CO_2 emissions and energy demand of a full hybrid vehicle. Energies. 2022;15;122. https://doi.org/10.3390/en15010122
[11] Kurtyka, K, Pielecha J. The evaluation of exhaust emission in RDE tests including dynamic driving conditions. Transp Res Proc. 2019;40:338-345. https://doi.org/10.1016/j.trpro.2019.07.050
[12] Lave LB, Seskin EP. Air pollution and human health. Science. 1970;169:723-733. https://doi.org/10.1126/science.169.3947.723
[13] Lee DI, Park J, Shin M, Lee J, Park S. Characteristics of real-world gaseous emissions from construction machinery. Energies. 2022;15;9543. https://doi.org/10.3390/en15249543
[14] Lim G, Lee S, Park C, Kim C, Choi Y. Combustion and emission characteristics of heavy-duty SI engine fueled with synthetic natural gas (SNG). SAE Technical Paper 2013-01-0026. 2013. https://doi.org/10.4271/2013-01-0026
[15] Mazanek A. An overview of engine and exploitation research methods taking into account the current and future quality requirements on motor fuels. Nafta-Gaz. 2014;8:534-540.
[16] Mądziel M. Liquified petroleum gas-fuelled vehicle CO_2 emission modelling based on portable emission measurement system, on-board diagnostics data, and gradient-boosting machine learning. Energies. 2023;16:2754. https://doi.org/10.3390/en16062754
[17] Mądziel M. Vehicle emission models and traffic simulators: a review. Energies. 2023;16;3941. https://doi.org/10.3390/en16093941
[18] Merkisz J, Lijewski P, Pielecha J. PEMS-based investigations into exhaust emissions from non-road and rail vehicles. Combustion Engines. 2016;166(3);46-53 https://doi.org/10.19206/CE-2016-339
[19] Merkisz J, Pielecha J, Fuć P. Badania i analizy zużycia energii i emisji zanieczyszczeń przez pojazdy w sieci drogowej (in Polish). Komitet Inżynierii Lądowej i Wodnej PAN. 2013;84.
[20] Napolitano P, Alfè M, Guido C, Gargiulo V, Fraioli V, Beatrice C. Particle emissions from a HD SI gas engine fueled with LPG and CNG. Fuel. 2020;269;117439. https://doi.org/10.1016/j.fuel.2020.117439
[21] Pelkmans L, Debal P. Comparison of on-road emissions with emissions measured on chassis dynamometer test cycles. Transport Res D-Tr E. 2006;11;233-241. https://doi.org/10.1016/j.trd.2006.04.001
[22] Porter B. Analysis of the timber transportation efficiency (in Polish). Technika Rolnicza Ogrodnicza Leśna. 2012;1. https://tech-rol.eu/index.php/pl/archiwum-2/2012
[23] Rahman SMA, Fattah IMR, Ong HC, Ashik FR, Hassan MM, Murshed MT et al. State-of-the-art of establishing test procedures for real driving gaseous emissions from light- and heavy-duty vehicles. Energies. 2021;14;4195. https://doi.org/10.3390/en14144195
[24] Ravanbakhsh M, Yousefi H, Lak E, Javed Ansari M, Suksatan W, Qasim QA et. al. Effect of polycyclic aromatic hydrocarbons (PAHs) on respiratory diseases and the risk factors related to cancer. Polycycl Aromat Comp. 2023; 43(9): 8371-8387. https://doi.org/10.1080/10406638.2022.2149569
[25] Real driving emissions: 2017 assessment of Portable Emissions Measurement Systems (PEMS) measurement uncertainty. JRC Technical Reports. 2018. https://doi.org/10.2760/127122
[26] Report European Automobile Manufacturers Association: Vehicles in use. Europe 2022.
[27] Rymaniak Ł, Kamińska M, Szymlet N, Grzeszczyk R. Analysis of harmful exhaust gas concentrations in cloud behind a vehicle with a spark ignition engine. Energies. 2021;14;1769. https://doi.org/10.3390/en14061769
[28] Sala R, Krasowski J, Dzida J. The influence of engine warm-up phase on nitrogen oxides emission for heavy-duty Euro VI diesel engine. MATEC Web Conf. 2017;118; 00035. https://doi.org/10.1051/matecconf/201711800035
[29] Siedlecki M, Fuć P, Sokolnicka B, Szymlet N. Analysis of the effect of exhaust aftertreatment systems configurations on the temperature measured in the exhaust system of a spark-ignition engine. Autobusy – Technika, Eksploatacja, Systemy Transportowe (in Polish). 2019;231. https://doi.org/10.24136/atest.2019.161
[30] Singh V, Biswal A, Kesarkar AP, Mor S, Ravindra K. High resolution vehicular PM10 emissions over megacity Delhi: relative contributions of exhaust and non-exhaust sources. Sci Total Environ. 2020;699;134273. https://doi.org/10.1016/j.scitotenv.2019.134273
[31] State Forest of Poland. https://www.lasy.gov.pl/en (accessed on 8.06.2024).
[32] Tang Q, Fu J, Liu J, Zhou F, Yuan Z, Xu Z. Performance improvement of liquefied natural gas (LNG) engine through intake air supply. Appl Therm Eng. 2016;103:1351-1361. https://doi.org/10.1016/j.applthermaleng.2016.05.031
[33] Thomas D, Li H, Wang X, Song B, Ge Y, Yu W et al. Comparison of tailpipe gaseous emissions for RDE and WLTC using SI passenger cars. SAE Technical Paper 2017-01-2391. 2017. https://doi.org/10.4271/2017-01-2391
[34] Tipanluisa J, Fonseca N, Casanova J, López J. Effect of n-butanol/diesel blends on performance and emissions of a heavy-duty diesel engine tested under the World Harmonized Steady-State cycle. Fuel. 2021;302;121-204. https://doi.org/10.1016/j.fuel.2021.121204
[35] Tzirakis E, Pitsas K, Zannikos F, Stournas S. Vehicle emissions and driving cycles: comparison of the Athens Driving

Cycle (ADC) with ECE-15 and European Driving Cycle (EDC). Global NEST J. 2006;8(3):282-290. https://doi.org/10.30955/gnj.000376
[36] Walendzik M, Łepkowski M, Nowacki G. Influence of road transport on the natural environment and threats involved in road goods transport (in Polish). Autobusy: Technika, eksploatacja, systemy transportowe. 2016;6.
[37] Wang X, Yan Y, Zhang C. Study of NH_3-SCR catalyst combinations based on diesel engine exhaust emission mechanisms. J Phys: Conf Ser. 2022;2329:012042. https://doi.org/10.1088/1742-6596/2329/1/012042
[38] Watson AY, Bates RR, Kennedy D. (ed.) Air pollution, the automobile, and public health. National Academies Press, Washington 1988. https://doi.org/10.17226/1033
[39] Więsik J. Technical equipment in forestry production. Machines and equipment for logging and transport of timber (vol. 2). Publishing House SGGW, Warsaw 2015.
[40] Xie J, Teng J, Fan Y, Xie R, Shen A. The short-term effects of air pollutants on hospitalizations for respiratory disease in Hefei, China. Int J Biometeorol. 2019;63(3):315-326. https://doi.org/10.1007/s00484-018-01665-y
[41] Zimkowska-Laskowska M, Laskowski P. Comparison of pollutant emissions from various types of vehicles. Combustion Engines. 2024,197(2), 139-145. https://doi.org/10.19206/CE-181193
[42] Ziółkowski A, Daszkiewicz P, Rymaniak Ł, Fuć P, Ukleja P. Analysis of the exhaust emissions from hybrid vehicle during RDE test. MATEC Web Conf. 2019;294:02002. https://doi.org/10.1051/matecconf/201929402002
[43] Ziółkowski A, Fuć P, Lijewski P, Rymaniak Ł, Daszkiewicz P, Kamińska M et al. Analysis of RDE emission measurements in rural conditions from heavy-duty vehicle. Combustion Engines. 2020;182(3):54-58. https://doi.org/10.19206/CE-2020-309

Maciej Bednarek, MEng. – Faculty of Civil and Transport Engineering, Poznan University of Technology, Poland.
e-mail: *maciej.bednarek@doctorate.put.poznan.pl*

Aleks Jagielski, MEng. – Faculty of Civil and Transport Engineering, Poznan University of Technology, Poland.
e-mail: *aleks.jagielski@doctorate.put.poznan.pl*

Andrzej Ziółkowski, DSc., DEng. – Faculty of Civil and Transport Engineering, Poznan University of Technology, Poland.
e-mail: *andrzej.j.ziolkowski@put.poznan.pl*

Maciej Siedlecki, DEng. – Faculty of Civil and Transport Engineering, Poznan University of Technology, Poland.
e-mail: *maciej.siedlecki@put.poznan.pl*