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DEVELOPMENT OF AN APPROACH TO THE CONSTRUCTION OF AN ADAPTED MODEL FOR ENSURING THE THERMAL READINESS PROCESSES OF A VEHICLE BASED ON FUEL CONSUMPTION AND EXHAUST GAS EMISSIONS

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The research object is the processes of changes in fuel consumption and harmful emissions of engines and vehicles during their operation.

The investigated problem consists in the lack of an approach to the construction of an adapted model for analytical studies of the thermal readiness processes of vehicles with petrol-powered engines.

An approach to ensuring vehicle thermal preparation based on fuel consumption and exhaust gas emissions is proposed. The essence of the improved algorithm and model lies in accounting for the specifics of warm-up processes based on the developed thermal preparation cycle for vehicle engines.

A feature of the improved approach is the incorporation of experimental research results and features of thermal preparation processes.

The field of practical application of the improved approach is the thermal readiness processes of vehicles with engines adapted to work on gasoline and LPG, focusing on fuel consumption and exhaust gas emissions.

Improvements have been made to the enlarged algorithm of the mathematical model for ensuring vehicle thermal preparation processes. This includes considering fuel supply and thermal readiness features, as well determining fuel consumption and emissions.

The peculiarity of the proposed model is that it allows systematic simulation of thermal preparation processes, taking into account factors and processes that cannot be investigated experimentally. This is validated by the model's adequacy test, showing that data deviation is within the statistical error range from 4.4 to 5.2 %.

The application of the developed approach ensures comprehensive consideration of the specifics of thermal preparation processes and supports decision-making for evaluating results according to the relevant criteria

Keywords: vehicle, thermal readiness, monitoring, enlarged algorithm, adapted model, fuel, emissions

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1. Introduction

The efficiency of motor fuel usage and the reduction of exhaust gas emissions from vehicle engines [1, 2] during start-up are influenced by numerous factors. These include climatic conditions [3], the type of fuel supply system [4], the availability and quality of pre-start preparation [5], the duration of pre-start preparation [6], and the presence of additional starting equipment [7, 8]. Moreover, operating conditions, such as engine and vehicle design [9, 10] and the timeframe for ensuring start-up readiness, play a crucial role [11].

The most common are single-fuel engines [12], operating exclusively on petrol or diesel [13, 14]. However, due to differences in production costs, vehicles are often converted from traditional fuels to more economical alternatives [15, 16]. Petrol vehicles adapted to operate on both petrol and liquefied petroleum gas (LPG) are particularly widespread [17, 18].

The start-up process of a vehicle engine adapted for petrol and LPG is unique [17, 18]. Typically, the engine starts on petrol and switches to LPG once the coolant temperature reaches around 45–50 °C [19, 20]. LPG, a mixture of approximately 50 % propane and 50 % butane [21, 22], is most effective in its liquid state [23]. A critical technical requirement for the efficient operation of such engines is the ability to maintain an optimal temperature range despite changes in ambient conditions [24, 25]. In cold climates, measures such as periodic idling or additional thermal preparation are commonly employed to ensure proper thermal conditions [26]. An essential aspect of vehicle operation is the moment when the engine begins to bear a load after prolonged inactivity [26, 27]. Ideally, this occurs when the coolant temperature reaches around 50 °C [17, 18]. To maintain the engine's optimal thermal state during inactivity, various thermal preparation methods are utilized [28]. Their effectiveness, however, varies depending on operating conditions and designs of engines and vehicles [29, 30]. For engines operating on both petrol and LPG, it may be advantageous to warm up the engine to the required temperature in pre-start mode without using vehicle fuel or idling [17, 18]. This enables an almost immediate switch to LPG operation with minimal or no reliance on petrol [17, 18].

Research aimed at reducing fuel consumption and minimizing the environmental impact of vehicle engines is both timely and critical for society, the environment, and the transportation sector. These efforts provide a valuable opportunity to improve vehicle warm-up processes under real-world conditions, especially for engines equipped with dual fuel systems. Enhancing these processes will not only improve operational efficiency but also foster better interaction between vehicles, infrastructure, and the environment, expanding the scope and quality of vehicle performance assessments.

2. Literature review and problem statement

Conventional petrol vehicles use the conventional method of warming up the engine while idling or driving. When using liquefied petroleum gas (LPG) as a motor fuel, the engine must be warmed up to around 45–50 °C when switching from petrol. This feature is crucial to ensure stable engine operation under operating conditions. When selecting methods to assess the fuel efficiency and environmental friendliness of vehicles during thermal preparation processes, all the factors mentioned earlier must be considered.

Thus, the described experimental research methods cannot always be fully and effectively applied to the study of such systems in difficult operating conditions. This is due to the peculiarities of the vehicle design, methods of data transmission, both within the vehicle and in the infrastructure environment, the specifics of applying cycles and experimental research methods [31]. When studying vehicle engines with a thermal storage device as part of a thermal readiness system, it is necessary to account for the features of the phase-change accumulator in information sources. The specifics of using a thermal accumulator in a vehicle are essential. However, it is more common to find data on studies solely focused on the thermal accumulator itself based on physical or laboratory models, or mathematical modeling [32, 33]. The design of vehicles, a wide variety of ways to transfer data within the vehicle between key units and control systems are the main problems of applying unification for diagnostic and experimental equipment. There is difficulty in assessing the fuel efficiency and exhaust emissions of a stationary vehicle. It lies in the fact that the on-board engine control system can only determine fuel consumption and exhaust gas emissions for a single component – CO. But this is only possible while the vehicle is in motion. Studying the operation peculiarities of vehicle thermal readiness systems in ambient conditions is a rather complicated and expensive task. The study is further complicated in terms of accounting for the design solutions of the phase-change thermal accumulator, estimating fuel consumption (petrol and LPG) and harmful emissions exclusively by experimental methods.

We note the widespread use of analytical components for various models and complexes of adapted programs specifically for the study of production, technological [34] and operational processes [35] of vehicle engines during thermal preparation periods. Various experimental methods are commonly used for research, especially in monitoring operational processes. In addition, special mechanisms and research methods are used to study thermal preparation systems based on phase-change thermal accumulators [36, 37]. Applying individual provisions from the reviewed works does not allow for a systematic assessment of vehicle fuel consumption and emissions during thermal preparation processes.

It is known that the calculation methods proposed in [38] can be used to study engine operating processes. This methodology and model enable successful calculation of the operating process of a vehicle and stationary engine. It also allows estimating exhaust gas emissions during engine operation in any mode. However, this methodology does not provide the possibility of operating an engine with a thermal preparation system and does not account for its features in terms of the components of the phase-change thermal accumulator, nor does it consider the use of different motor fuels under operating conditions.

The paper [39] also describes a method for calculating the operating process of an internal combustion engine. This method has significant drawbacks associated with the inability to assess the performance of a thermal preparation system based on a thermal accumulator during the operation of a regular engine. A fairly convenient method for evaluating the state parameters of a gas internal combustion engine is described in [32], but it suffers from the same shortcomings as those outlined for [33]. In the study described in [35], the above models and methods for evaluating the thermal preparation parameters of a vehicle engine in the pre-start processes are either significantly inconvenient or not feasible at all. This is because the engine with the proposed thermal preparation system is not started at all during pre-start warm-up. Therefore, evaluating thermal preparation parameters can only be done by the indicators of the thermal preparation system based on a thermal accumulator. In addition to the above, there are problems with the systematic assessment of the parameters of thermal preparation, fuel consumption (petrol and LPG) and exhaust gas emissions of engines. The complexity lies in performing such evaluations under real-world operating conditions, considering various methods of implementing thermal preparation of engines and vehicles.

The features of implementing thermal preparation in the presented paper are as follows: the operation of the additional thermal preparation system for the vehicle is based on using a coolant from (through) the thermal accumulator for the appropriate time interval. This interval is necessary to heat the engine from the ambient temperature to 50 °C. The engine is not running at all. The pre-start thermal preparation is carried out using a phase-change thermal accumulator and the heat stored in the substance from previous vehicle operation. To eliminate the shortcomings mentioned above, the mathematical model described in [35, 36] can be used as a basis. The mathematical model and method [35, 36] allow for evaluating thermal preparation parameters of both idling and running engines on different fuel types (both petrol and LPG). Furthermore, the mathematical model anticipates the additional use of a thermal accumulator. However, the model [36] does not fully account for experimental data on real warm-up processes under vehicle operating conditions.

Thus, there are many unresolved problems and issues regarding the organization of thermal preparation modes and design features of the experimental vehicle and the application of existing mathematical models. Based on the conducted analysis, there is a clear need to develop (improve existing) analytical mechanisms for systematically determining and evaluating fuel, environmental and operational indicators for engines and vehicles. This is essential for vehicles equipped with thermal preparation systems converted to run on petrol and LPG under real-world conditions.

3. The aim and objectives of the study

The aim of the study is to develop a basic approach for conducting an analytical study of the starting processes of a vehicle equipped with elements of a thermal readiness system based on a phase-change thermal energy storage, focusing on fuel consumption and exhaust gas emissions. This will enable the investigation and determination of indicators and parameters characterizing fuel consumption and exhaust gas emissions during pre- and post-start thermal preparation processes of a vehicle equipped with a thermal preparation system in different operating modes.

To achieve the aim, the following objectives were accomplished:

– the use of the adapted model for ensuring vehicle thermal readiness processes was substantiated;

– basic approaches were developed for forming an algorithm, along with key assumptions and model representations, to improve the assessment of fuel efficiency and environmental performance of a vehicle under operating conditions;

– the enlarged algorithm of the mathematical model for analyzing fuel consumption and emissions in engines equipped with a thermal readiness system was refined;

– the features of the calculation program were justified, and studies were conducted on fuel consumption and emissions in engines equipped with thermal readiness systems;

– the results of applying the developed mathematical model to study fuel consumption and emissions in such engines were presented, including an evaluation of its potential implementation in various interconnected research components.

4. Materials and methods

The object of this research is the processes of changes in fuel consumption and harmful emissions of engines and vehicles during their operation.

The subject of the study is the identification of ways, approaches, and methods for analytical research into the thermal readiness processes of a vehicle with an engine adapted for operation on petrol and LPG, focusing on fuel consumption and exhaust gas emissions.

The main hypothesis of the study is that reliable results on vehicle thermal readiness can be obtained by utilizing appropriate tools and methodologies for analytical evaluation of its stages, approaches, and processes, particularly in terms of engine fuel consumption and emissions.

The assumptions underlying the study are aimed at exploring methods, approaches, and techniques for analyzing the thermal readiness processes of a vehicle with a petrol- and LPG-adapted engine, focusing on operational fuel consumption and emissions.

The research methodology incorporates experimental methods, data exchange, and monitoring, alongside a systematic approach to developing schemes and stages for thermal preparation. This includes analyzing internal combustion engine processes, applying heat transfer and heat accumulation theories, conducting system energy analysis, and performing parametric identification. The results are validated by comparing calculated data with experimental outcomes, ensuring the adequacy of the mathematical model and the study's conclusions.

5. Results of research, development, and analytical study of vehicle start-up processes by fuel consumption and exhaust gas emissions

5. 1. Justification for the use of the adapted model for ensuring vehicle thermal readiness processes

One effective method for improving the efficiency and environmental friendliness of vehicle engines is the use of thermal preparation systems based on phase-change thermal energy storage [40, 41]. The relevant measures can enhance fuel efficiency [42, 43] and reduce harmful emissions [44, 45] during pre-start thermal preparation and vehicle warm-up processes.

However, this raises questions regarding the efficiency and accuracy of evaluating fuel consumption and emissions during this period [46, 47]. It is necessary to consider thermal preparation modes and fuel consumption, both liquid oil and LPG [48]. Special methods for determining performance indicators and means of obtaining them must also be applied [49, 50]. Additionally, it is crucial to account for the specifics of obtaining this data [51, 52] in modern vehicles [53, 54], particularly in their systemic interaction with infrastructure [52] and the environment. In this context, it is advisable to examine information exchange not only with transport infrastructure [55, 56] but also with road infrastructure [49, 51] and the environment.

During the experimental study, various data within the vehicle's information system were used [17, 18]. These included parameters obtained through remote monitoring of the vehicle and engine state parameters, as well as direct measurement and remote transmission of thermal state parameters using additional built-in sensors [17, 18].

The remote vehicle monitoring information system was developed and implemented to study the thermal readiness processes of an engine with a thermal storage device [17, 18] in the environment. The scheme of data exchange between the components of the engine remote monitoring information system is given in [17].

Fig. 1 shows a functional diagram of the interaction between the standard vehicle engine control system and elements of the remote monitoring system for thermal readiness processes [37, 40, 46, 49].

The study required remote monitoring of the engine parameters and remote transmission of the thermal readiness system parameters using additional sensors. For this purpose, an OBD-II adapter (scanner) and a monitoring module developed by the authors based on a GSM tracker were utilized. Data exchange within the monitoring information system was conducted through GPS, GPRS, a-GPS, SBAS, Galileo, the Internet, or a local network, facilitating the transmission of both digital and analog data [17, 18].

According to Fig. 1, the model $M_{\sum M}$ of the database for the vehicle monitoring system (with an engine equipped with a thermal readiness system) was developed, consisting of 2 subsystems. These subsystems provide signals from the main information blocks of both the vehicle and the engine, as well as the thermal readiness system.

The first subsystem M_{M1} includes units for collecting and transmitting data via the CAN bus from the vehicle about its condition, from the engine about its condition and from the vehicle about its operating conditions. The second subsystem M_{M2} includes units for collecting and transmitting data via a GSM tracker from the engine thermal readiness system about the vehicle status, the system status monitoring tools about the vehicle operating conditions and monitoring devices. Both subsystems form a unified information field that characterizes the processes of remote monitoring of the vehicle with a thermal readiness system [17, 18]. The peculiarity of this integration lies in the ability of the subsystems, based on their specific tasks, to operate independently within the information field while still forming a single information field [46, 49].

The domain model for monitoring and collecting data in the system is represented separately for each subsystem as corresponding sets. Set 1 – base vehicle, base vehicle engine, and their operating conditions. Set 2 – experimental thermal readiness system, base vehicle, monitoring components, and their operating conditions. Thus:

$$M_{\sum M} = \begin{cases} M_{M1} = \left\langle \begin{matrix} O_{M.1}, V_{M.in.1}, V_{M.out.1}, \\ F_{M.1}, H_{M.1}, P_{M.1}, R_{M.1} \end{matrix} \right\rangle, \\ M_{M2} = \left\langle \begin{matrix} O_{M.2}, V_{M.in.2}, V_{M.out.2}, \\ F_{M.2}, H_{M.2}, P_{M.2}, R_{M.2} \end{matrix} \right\rangle, \end{cases} \tag{1}$$

where, within subsystems, respectively: O_{M1} and O_{M2} – automation objects in the system represented as independent components; V_{M1} and V_{M2} – information elements (input and output data) of the system components; F_{M1} and F_{M2} – automation functions performed by the system and for forecasting the parameters of the system components; H_{M1} and H_{M2} – system data processing and forecasting of system components' parameters; P_{M1} and P_{M2} – value sets characterizing the personnel ensuring system operation and forecasting of system components' parameters; R_{M1} and R_{M2} – sets of relations (interrelations) among the domain components (system components) [17, 18].

The peculiarity of the experimental vehicle was its engine being equipped with an external heat exchange system incorporating a phase-change thermal accumulator (PTA) as a heat storage device under operating conditions. Using this system based on designed thermal cycles has achieved many results. Namely, reduced the time of engine thermal readiness to the start-up temperature, lowered fuel consumption (liquid and LPG), and decreased exhaust gas (EG) emissions.

To study the thermal readiness processes of a vehicle engine capable of running on petrol and LPG, a thermal preparation cycle was used [17, 18]. It is designed to implement thermal readiness in the modes of engine pre-start and post-start warm-up [46, 49]. In addition, 4 main thermal readiness modes of an engine and vehicle were used in the study [17, 18]:

1. Thermal readiness of a stationary vehicle with an engine running at minimum idle.
2. Thermal readiness of a stationary vehicle with the engine running at minimum idle, with electrical consumers and interior heating exchanger engaged.
3. Thermal readiness of a stationary vehicle with the engine running at minimum idle and in motion.
4. Thermal readiness of a vehicle in motion.

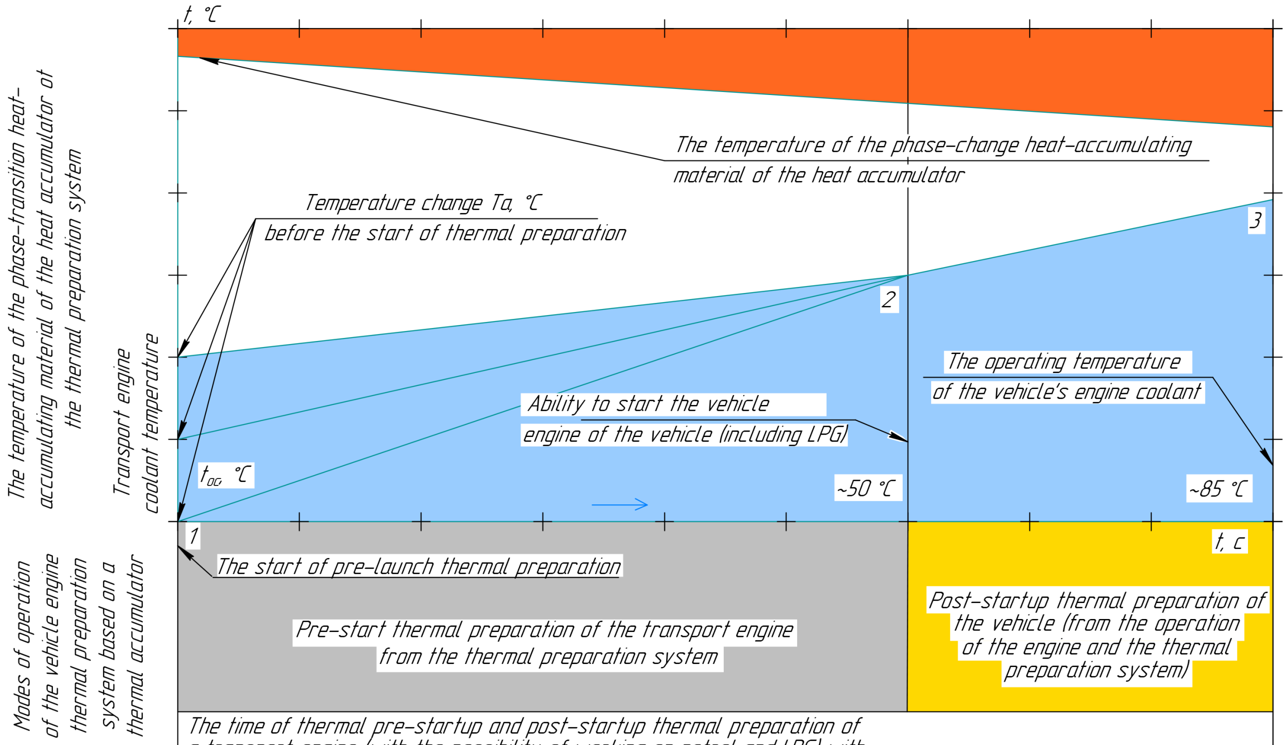
These modes provide comprehensive pre-start thermal preparation, raising the temperature from ambient levels to the point required for starting the engine [17, 18]. Additionally, after engine start-up, the process continues until the engine reaches a coolant temperature of +50 °C [17, 18]. Following this, further thermal preparation is achieved through the combined use of heat from the running engine and the thermal energy stored in the phase-change thermal accumulator, until the temperature reaches +85±5 °C. The full cycle of engine thermal preparation is described in detail in [17, 18].

To justify the necessity of applying analytical methods for studying the thermal preparation processes of a vehicle engine [18], in addition to experimental, the lower part of Fig. 2 shows the possibilities of obtaining data through experimental means. These methods provide data about the components of the described study.

For the mode labeled "1 – Thermal readiness of a stationary vehicle with the engine running at minimum idle speed", thermal preparation parameters and indicators can be determined experimentally. However, it is not feasible to experimentally determine the parameters and indicators of fuel efficiency (for both petrol and LPG) and exhaust gas emissions of the engine in idle mode. This limitation highlights the specific challenges associated with obtaining and interpreting data through the CAN bus from the engine control unit for a stationary vehicle. This is achieved by configuring the standard vehicle engine control system accordingly.

Mode "2 – Thermal readiness of a stationary vehicle with the engine running at minimum idle speed, with electrical consumers and interior heating exchanger engaged". In this mode, thermal preparation parameters and indicators can be determined experimentally. However, it is not possible to experimentally determine the parameters and indicators of fuel efficiency (for both petrol and LPG) or exhaust gas emissions of the engine "in minimum idle mode". These limitations highlight the specifics of obtaining and analyzing data via the CAN bus from the control unit for a stationary vehicle, which relies on the vehicle's standard engine control system settings.

Fig. 1. Functional diagram of the interaction between the standard vehicle engine control system and elements of the remote monitoring system for thermal readiness processes



The time of thermal pre-startup and post-startup thermal preparation of a transport engine (with the possibility of working on petrol and LPG) with a thermal preparation system based on a phase-change thermal accumulator

Experimental regimes of thermal preparation of a transport engine under operating conditions

Obtaining information about the components of the study in the modes of monitoring the vehicle and measuring state parameters:

Monitoring of vehicle parameters			Measurement of parameters and indicators of the technical condition of the vehicle		
fuel efficiency	thermal training	emissions of harmful substances	fuel efficiency	thermal training	emissions of harmful substances
1. Thermal preparation of a stationary vehicle in idle mode					
–	+	–	–	+	–
2. Thermal preparation of a stationary vehicle in idle mode with electrical consumers and interior heating exchanger engaged					
–	+	–	–	+	–
3. Thermal preparation of a stationary vehicle in idle mode and in motion					
–/+	+	–/+	–/+	+	–/+
4. Thermal preparation of a vehicle in motion (warming up in motion)					
+	+	+	–/+	+	–/+

" – " – not possible, limitedly possible, not fully possible;
" + " – possible;
"–/+" – not possible / possible – only for certain processes

Fig. 2. Thermal preparation cycle of a vehicle with an engine modified for operation on petrol and LPG, equipped with a thermal preparation system based on a phase-change thermal accumulator, under operating conditions with the justification of experimental research and the approach to ensuring vehicle thermal preparation processes by fuel consumption and exhaust gas emissions

Mode "3 – Thermal readiness of a stationary vehicle with the engine running at minimum idle and in motion". For this mode, thermal preparation parameters and indicators can be determined experimentally. It is partially possible to experimentally obtain the parameters of fuel efficiency (for both petrol and LPG) and exhaust gas emissions of the engine. For a stationary vehicle "in minimum idle mode", these measurements are not feasible. However, for the "in motion" part of the experimental mode, it is fully possible to determine the parameters of engine fuel efficiency and exhaust gas emissions. Yet, emission parameters are limited to a single component, CO, due to restrictions imposed by the factory settings of the vehicle's standard engine control unit. These constraints underscore the specifics of obtaining data via the CAN bus from the control unit for a stationary vehicle and in motion, as governed by the vehicle's standard engine control system settings.

For the mode "4 – Thermal readiness of a vehicle in motion", thermal preparation parameters and indicators can be determined experimentally. Partial experimental determination of fuel efficiency parameters (for both petrol and LPG) and exhaust gas emissions of the engine is also feasible. However, for a stationary vehicle, it is not possible to determine fuel efficiency parameters (for both petrol and LPG) at the time of engine start-up. In most cases, during the "in motion" test mode, fuel efficiency parameters can be determined. Conversely, for a stationary vehicle at engine start-up, determining exhaust gas emissions is not possible. For most of the "in motion" experimental mode, emissions parameters can only be obtained for a single component – CO. This limitation stems from the factory settings of the vehicle's standard engine control unit, which restrict the parameters of exhaust gas emissions that can be measured. These constraints explain the specific challenges in obtaining data via the CAN bus from the control unit for a vehicle in motion, using the vehicle's standard engine control system settings.

It can therefore be confidently stated that conducting research solely through experimental methods under operating conditions to study the thermal readiness processes of a vehicle engine is not feasible. There is a need to develop new analytical programs or enhance existing ones for calculating the engine's operational processes under real-world conditions. This should include considerations for the vehicle's thermal preparation system, which is based on a phase-change thermal accumulator, as well as the specifics of test cycles, operational modes, and the potential for future research on similar systems.

When studying the thermal readiness system of a vehicle engine in operation, there is a pressing need to refine and adapt current approaches to research, integrating both experimental and analytical methods. Real-world operating conditions, fuel use characteristics, vehicle design, and the incorporation of a thermal readiness system utilizing a phase-change thermal accumulator demand specialized research methodologies. Similarly, the unique challenges of obtaining data through monitoring and direct measurement of parameters necessitate tailored research approaches. The inability to uniformly access and implement studies of all indicator groups (parameters) across different thermal preparation modes introduces additional limitations. This underscores the necessity of analytical computational methods and algorithms for these vehicle studies. Such tools are essential to account for the specific operational characteristics during pre- and post-start warm-up, including fuel types, design configurations, operating conditions, and ambient temperatures. This refined approach and model adaptation will enhance the evaluation accuracy of fuel consumption and exhaust gas emissions of engines under real-world operating conditions.

5. 2. Main approaches to the formation, assumptions and model representations of the improved algorithm and mathematical model

To formulate the approach, algorithms for implementing mathematical models of vehicle engines for similar purposes were analyzed. This included the development or improvement of analytical mechanisms for systematically determining and evaluating fuel efficiency, environmental impact, and operational indicators of engines during thermal preparation. These engines are designed to operate on both petrol and LPG under real-world conditions.

To estimate fuel consumption and exhaust gas emissions, the algorithm and model of the "Engine-neutralizer" system were selected as the basis [33–36, 48]. The engine's notable features included its ability to operate on petrol and LPG, as well as the integration of a phase-change thermal accumulator (TA) directly into the cooling system to ensure thermal readiness processes. The evaluation model of the engine's operational process during thermal preparation under various conditions is represented by differential and algebraic dependencies. It is based on determining the engine operating modes when the vehicle is conditionally driven on a formal driving cycle. The model also incorporates experimentally measured engine performance indicators corresponding to these modes. Using this data, it calculates fuel consumption and exhaust gas emissions for specific sections of the vehicle's movement and for the driving cycle as a whole [18, 33–36, 48].

This approach addresses key limitations inherent in vehicle design and experimental studies under operating conditions. It integrates three interrelated research components: informational, analytical, and energy, allowing for comprehensive implementation in terms of fuel consumption and exhaust gas emissions of engines. This integration is applied across the four primary thermal readiness modes of the engine and vehicle described above.

The algorithm and mathematical model [18, 33–36, 48] are designed to study vehicle performance for engines operating on petrol and LPG:

– under various driving cycles, including the New European Driving Cycle (NEDC) and the European Urban Driving Cycle, as well as in compliance with UNECE Regulations 83–05 [33–36, 48, 57];

– under various thermal preparation modes of the test vehicle, ranging from city-based warm-up to warm-up during route driving [23, 58–60].

This driving cycle is typically used to assess vehicle environmental safety, exhaust gas emissions, and fuel consumption. The formal cycle includes four elementary urban segments covering 4.052 km in 780 seconds at an average speed of 50 km/h, followed by a mainline cycle covering 6.955 km in 400 seconds at a maximum speed of 120 km/h [1, 57, 58].

To evaluate the impact of operating conditions, specifically ambient temperature, on the efficiency of the thermal readiness system based on a phase-change thermal accumulator, analytical studies were conducted at ambient temperatures of –20 °C, 0 °C, and +20 °C. These conditions differ from the standard driving cycle testing temperature of +20 °C. Consequently, the results of the computational study cannot be directly applied to meet environmental standards but serve to assess the effectiveness of the developed thermal preparation system under real-world operating conditions. The algorithm and mathematical model for driving cycle simulations are based on determining the required engine torque M_e and crankshaft speed n_e. These values correspond to vehicle speed V_a and acceleration j_a.

During acceleration segments of the driving cycle, the algorithm calculates the engine torque and speed at the start and end of each section under quasi-stationary conditions. It assumes a linear dependence of engine performance changes. When the vehicle is decelerating in forced idling mode with the clutch engaged, the standard engine control system cuts off the fuel supply. In such cases, the algorithm assumes zero engine torque, fuel consumption, and emissions. For deceleration with the clutch disengaged, the algorithm assumes that the engine shaft speed corresponds to the minimum idle speed of the test vehicle engine. To implement this algorithm, it is necessary to identify and formulate key assumptions and model representations.

The object of the study was a KIA Ceed 2.0 5MKP passenger vehicle equipped with a G4GC engine [17, 18]. It was additionally fitted with 4th-generation gas cylinder equipment for LPG operation, configured to switch to LPG at a coolant temperature of 40 °C (as per system settings). The standard vehicle engine cooling system includes two cooling circuits, a pump, a thermostat, a cooling radiator, and an interior heater radiator [11, 17, 18]. Detailed specifications, parameters, and compliance with remote monitoring capabilities are provided in [17, 18].

The installed 4th-generation LPG equipment was designed to enable the vehicle to operate on LPG while adhering to all applicable regulations and possessing a certificate of conformity. This system allows the engine to function on petrol under the same conditions as a standard petrol-powered engine. The LPG system features synchronized gas injection for each cylinder, utilizing electromagnetic gas injectors that deliver gas similarly to a petrol injection system. Fuel dosing and injection phase determination are controlled by the vehicle's standard onboard controller [17, 18]. The configuration of the thermal preparation system, including the location of the phase-change thermal accumulator and positions of additional temperature sensors within the vehicle's engine cooling system, is described in [17].

To apply the improved model based on the "Engine-neutralizer" system [33–36, 48], assumptions and model representations are introduced into the research system model for the relevant groups:

1. Key assumptions regarding the formation and operation of the thermal preparation system (TPS) in a vehicle engine converted to run on petrol and LPG as part of the PTA in accordance with the program (algorithm) are as follows:

a) the pre-start thermal preparation of the engine using the TPS begins with discharging the PTA from the temperature at which the heat storage material (HSM) has accumulated the operating temperature (the mode is determined by the HSM characteristics);

b) the engine starts on either petrol or LPG automatically upon reaching the temperature of possible load acceptance. It is determined by the coolant temperature, at which it is possible, in accordance with the engine manufacturer's instructions;

c) the engine starts and operates in idle mode (hereinafter referred to as idle) in a steady state. The engine operation in idle mode occurs at $n_{i.s.}$=1,000 min^{-1} at the ambient temperature (set by the initial data in the algorithm and mathematical model);

d) after a complete stop, the engine operates in idle mode until the PTA is fully charged and the required TAM temperature is reached (set by the TAM output parameters when forming the algorithm and mathematical model);

e) based on the results of monitoring the coolant thermal parameters in the engine cooling system, it is assumed that engine operation aligns with the monitoring results. This applies to both petrol and LPG engine operation with a TPS at different ambient temperatures.

2. Assumptions and model representations for building an algorithm and mathematical model of the TPS functioning of the accepted design of the engine thermal readiness system:

a) the thermal state of a vehicle engine capable of running on petrol and LPG with a TPS is assessed by the time-varying temperature of its parts in contact with the coolant;

b) the operation of the TPS at varying ambient temperatures will occur uniformly under the same state parameters and depends only on the thermal insulation properties of its components;

c) during the discharge of fuel assemblies, heat losses to the environment from pipes are negligible. This is because the coolant temperature at the TPS inlet equals the temperature at the engine outlet. At this time, the engine runs on either petrol or LPG. In this case, the coolant temperature at the TPS outlet is equal to the temperature at the engine inlet;

d) similarly to assumption (c), heat losses to the environment from the TPS during its discharge and heat losses for heating other units simultaneously with the engine are not taken into account;

e) the heat transfer coefficients (thermal conductivity) and specific heat capacities in the TPS are constant and will not depend on temperature. The heat transfer coefficients of the coolant in the TPS heat exchanger circuits are the same;

f) at the initial time $\tau=0$ during TPS discharge, the heat storage material is in a liquid state, with a uniform temperature throughout the TPS volume, equal to the temperature of the heat storage material itself;

g) the heat exchange between the heat storage material and the fuel assemblies housing it will be uniform over the entire material surface. The same is true for external insulation in contact with the environment. Heat losses through connections and communications are negligible.

5. 3. Improved enlarged algorithm of the mathematical model for ensuring vehicle thermal preparation processes

An improved enlarged algorithm to study fuel consumption and exhaust gas emissions of a vehicle engine converted to run on petrol and LPG, with a thermal preparation system, is shown in Fig. 3. The enhanced components of the improved enlarged algorithm are highlighted in gray in the background of the algorithm in Fig. 3. Before calculations, initial data are entered into blocks 1–3, 5, 6. In block 1, engine parameters (Table 2) are entered, and in block 2 – parameters of the vehicle (Table 1) running on petroleum liquid fuel (petrol) and LPG, respectively.

The main parameters of the vehicle and engine are as follows: piston stroke, s, m; connecting rod length, l, m; compression ratio, ε; cylinder diameter, d, m; number of cylinders, i; atmospheric pressure, p_0, Pa; ambient temperature, T_0, °C. Working fluid parameters: lower heating value of fuel, H_u, J/kg; stoichiometric air-fuel ratio, l_0, kg/kg. Design parameters: engine gas distribution phases, $\varphi_{e.o.}$, $\varphi_{in.o.}$, $\varphi_{e.v.}$, $\varphi_{in.v.}$, degrees c.r.; number of intake and exhaust valves, i_{in}/i_{ex}, units; intake and exhaust valve head diameters, d_{in}/d_{out}, mm. Additionaly: main and connecting rod journal diameter, d_1/d_{12}, mm, piston pin diameter, d_{23}, mm; number of compression and oil rings, i_r. Structural: weight of the vehicle and driver, kg, frontal cross-sectional area of the vehicle, m^2, wheel radius, m, aerodynamic drag coefficient. Also: 1–5th gear and final drive ratio, transmission efficiency. Block 3 contains the road and environmental parameters: atmospheric pressure, p_0, Pa, road resistance coefficient, ψ, ambient temperature, T_0, K. In block 4, parameters of vehicle movement on the route are entered (under the provisions of Fig. 3). In block 5, parameters of the thermal readiness system of engines capable of running on petrol and LPG, equipped with a phase-change thermal accumulator, parameters and properties of the materials of their components are entered. Blocks 6–8 prepare output data for the "Engine-neutralizer" mathematical model.

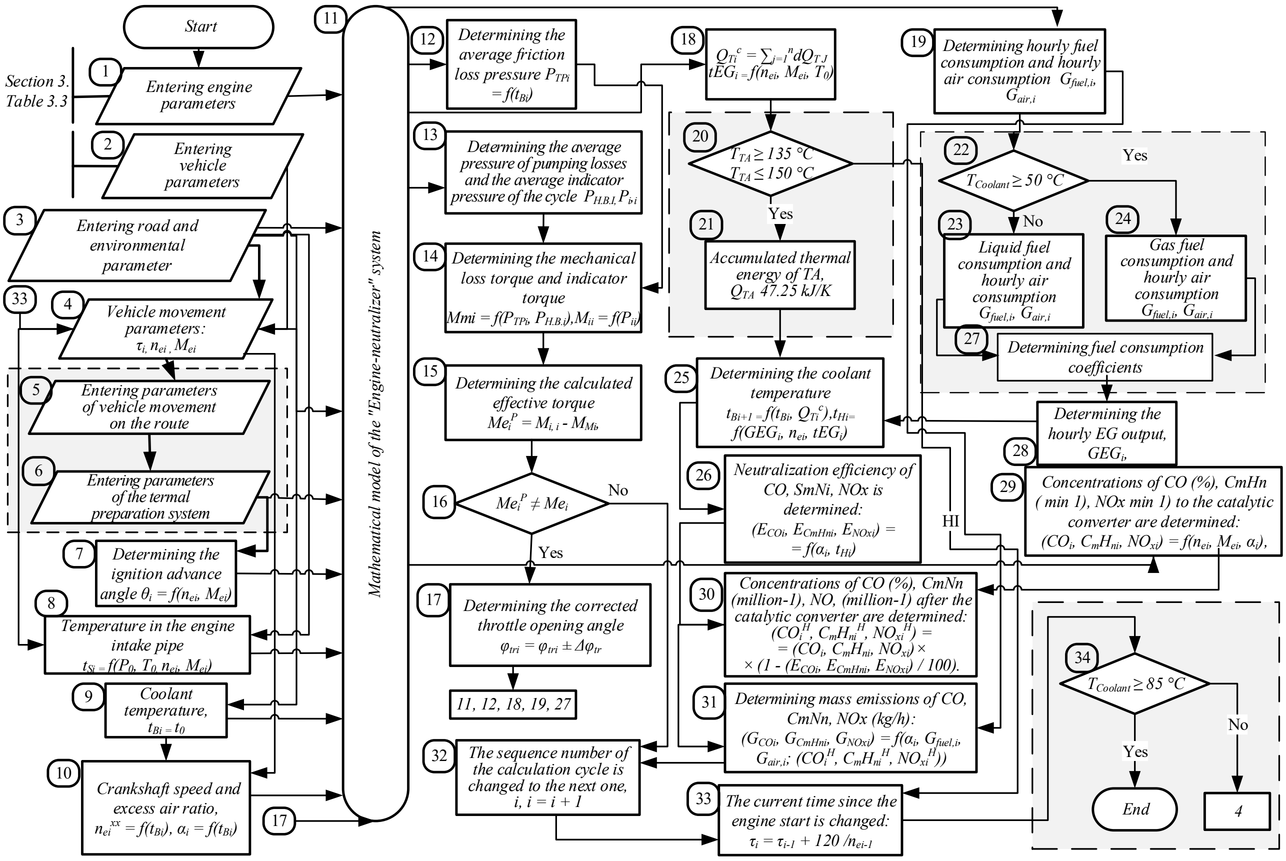


Fig. 3. Overview of the enlarged improved algorithm for analyzing fuel consumption and emissions of a vehicle engine adapted for petrol and LPG operation, equipped with a thermal preparation system incorporating a phase-change thermal accumulator

Block 6 defines the parameters of the driving mode and operation of a vehicle engine converted to run on petrol and LPG at the relevant time. They include: τ_i – time since engine start, *s*, n_{ei} – engine crankshaft speed, min^{-1}, M_{ei} – engine effective torque, N·m. Block 7 determines the ignition advance angle θi, degrees c.r. as a function of $\theta i=f(n_{ei}, M_{ei})$. Block 8 determines the temperature of the engine intake pipe $t_{Si}=f(P_0, T_0, n_{ei}, M_{ei})$, K. In block 9, the initial coolant temperature is determined, $t_{Bi}=t_0$. Block 10 determines the idle crankshaft speed n_{ei}^{idle} and excess air coefficient as a function of t_{Bi}, $n_{ei}^{idle}=f\left(t_{Bi}\right)$, $\alpha_i=f(t_{Bi})$.

Table 1

Specifications of the KIA CEE’D 2.0 5MT vehicle [17, 18]

No.	Parameter	Value
1	Gross weight with driver, kg	1,500
2	Engine size, cm^3	1,975
3	Maximum speed, km/h	205
4	Combined fuel consumption, l\100 km	7.1
5	Engine power, hp (kW)/min^{-1}	143 (105)/6,000
6	Aerodynamic drag coefficient	0.3
7	Dynamic wheel radius, m	0.285
8	Transmission type	manual 5
9	First gear ratio	3.308
10	Second gear ratio	1.962
11	Third gear ratio	1.257
12	Fourth gear ratio	0.976
13	Fifth gear ratio	0.778
14	Final drive ratio	4.188

Table 2

Specifications of the G4GC engine of the KIA CEE’D 2.0 5MT vehicle [17, 18]

No.	Parameter	Value
1	Cylinder diameter, mm	82
2	Piston stroke, mm	93.5
3	Connecting rod length, mm	150,01
4	Compression ratio	10.1:1
5	Number of cylinders	4
6	Stoichiometric air-fuel ratio, kg	14.7
7	Exhaust valve head diameter, mm	26.5
8	Intake valve head diameter, mm	31.0
9	Number of intake valves, units	8
10	Number of exhaust valves, units	8
11	Lower heating value of fuel, J/kg	43.70·10^6
12	Main journal diameter, mm	56.942–56.962
13	Connecting rod journal diameter, mm	44.946–44.966
14	Piston pin diameter, mm	20.001–20.006

The prepared output data are submitted to block 11, where calculations are performed using the "Engine-neutralizer" mathematical model [33–36, 48]. For analytical and computational studies within the improved algorithm and, under the provisions of the algorithm and the "Engine-neutralizer" model, two specialized models are used in parallel. These models have been adapted to work together.

These are the "Petrol engine-neutralizer" and "Gas engine-neutralizer" (LPG) mathematical models [33–36, 48]. After exiting the "Engine-neutralizer" model, further calculation is performed in 3 directions, where operations are sequentially carried out to determine the energy, fuel efficiency, and environmental performance of an engine converted to run on petrol and LPG. The algorithm and the "Engine-neutralizer" mathematical model are based on the functional structure of the system described in [33–36, 48]. The modeling of the ICE workflows was based on the volume balance method proposed in [10, 38, 39]. The mechanical friction losses of the engine were determined using the theory of machines and mechanisms. The parameters of the "Engine-neutralizer" system that ensure its efficiency include the coolant temperature of the engine. It is determined depending on the ambient temperature and the main heat flows from the walls of the engine cylinder and combustion chamber. In addition, flows of the heat exchange part of the thermal readiness system based on the heat storage device – phase-change thermal accumulator and the operation of the temperature control system are considered, °C. The corresponding values are calculated for both petrol and LPG, respectively. Therefore, the coolant temperature of a vehicle engine capable of running on petrol and LPG is:

$$t_{COOL_1} = (T_0 - 273) + \int_0^{\tau_{HP_{1i}}} \frac{(q_T(\tau)i + q_{TA1}(\tau))}{m_{COOL_1} \cdot c_{COOL_1}} \mathrm{d}\tau, \tag{2}$$

where $\tau_{HP_{1i}}$ is the time to complete heating of the engine when operating on the corresponding fuel: petrol or LPG, s; $q_T(\tau)i$ is the heat flow to the coolant from the wall of the engine (on the corresponding fuel type: petrol or LPG) cylinder and combustion chamber, W; $q_{TA1}(\tau)$ – heat flow to the coolant from the heat exchange part of the storage device – thermal accumulator of the thermal readiness system, W; m_{COOL_1} – coolant mass, kg; c_{COOL_1} – coolant heat capacity, J/(kg·K).

When the engine operating temperature rises to 85 °C, the increase is slowed down by the automatic operation of the control system. The heat flow from the walls of the vehicle engine cylinders and combustion chamber to the coolant is determined when calculating the engine operating cycle in block 28 of the algorithm (Fig. 3). The heat flow passing through the heat exchange part of the storage device to the engine coolant is determined using dependency (2). The maximum temperature in the catalytic converter is determined by considering the ambient temperature, based on the temperature and mass flow of exhaust gases, °C, [7, 10, 18, 48]:

$$\begin{gathered} t_{CAT} = (T_O - 273) + \\ + \int_O^{\tau} \frac{G_{ET}(\tau)i \cdot C_{EG}(t_{EG})i \cdot (t_{EG}(\tau)i - t_{CAT})}{m_{CAT} \cdot C_{CAT}(T_{CAT})} \mathrm{d}\tau, \end{gathered} \tag{3}$$

where $C_{EG}(t_{EG})i$ is the heat capacity of exhaust gases for different fuels (petrol and LPG), J/(kg·K); $G_{EG}(\tau)i$ is the mass flow of exhaust gases, also calculated for different fuels, kg/s; $t_{EG}(\tau)i$ – temperature of the engine exhaust gases also for different fuels, K; $C_{CAT}(t_{CAT})$ – heat capacity of the catalytic converter, J/(kg·K); m_{CAT} – mass of the catalytic converter unit, kg.

The mass flow of exhaust gases is determined when calculating the engine performance (workflow). This takes into account the data from blocks 28 and 31 of the algorithm. The operating temperature is calculated when determining the engine performance and in accordance with its operating mode. The efficiency of the catalytic converter unit is determined taking into account the excess air coefficient and the catalytic converter unit temperature. To form a mathematical description of the effect of the catalytic converter temperature on the quality (efficiency) of exhaust gas neutralization, an exponential relationship was determined. It was based on experimental data on substance conversion in the catalytic converter unit depending on the temperature of the catalytic converter unit of a vehicle engine [17, 18]. Then the engine neutralization efficiency for the *i*-th substance [7, 10], %:

$$E_i = E_i(\alpha)i \cdot E_i(t_{CAT})i = E_i(\alpha) \cdot \left(1 - e^{-30 \cdot \left(\frac{t_{CAT} - 77}{200}\right)_4}\right), \tag{4}$$

where $E_i(\alpha)i$ is the neutralization value for the *i*-th harmful substance depending on the fuel-air mixture composition and type of fuel [7, 10], %; $E_i(t_{CAT})i$ is the neutralization efficiency for the *i*-th harmful substance depending on the temperature of the catalytic converter unit and the type of fuel used in the engine.

If the temperature of the catalytic converter unit is less than 77 °C, its efficiency is zero. The obtained analytical dependencies for determining the engine and catalytic converter temperatures and the neutralization efficiency of harmful substances for different fuels are used to study the fuel efficiency and environmental performance of a vehicle. This includes warming up the engine capable of running on petrol and LPG and the catalytic converter. The warm-up occurs from ambient temperature to the operating temperature when using a thermal readiness system based on a thermal storage device – phase-change thermal accumulator.

Block 12 determines the average mechanical friction loss pressure in the engine, $P_{TPi}=f(t_{Bi})$, Pa. After that, in block 13, we determine the average pumping loss pressure $P_{H.B.i}$; Pa, and also the average cycle indicator pressure $P_{i,i}$, Pa, of the engine. In block 14, we determine the mechanical friction loss torque $M_{Mi}=f(P_{TPi}, P_{H.B.i})$, N·m, and the indicator torque $M_{ii}=f(P_{ii})$, N·m, of the engine. In block 15, the effective torque is calculated: $M_{eiP}=M_{i,i}-M_{Mi}$, N·m. In block 16, the correspondence between the calculated M_{eiP} and the effective torque for the engine M_{ei} is checked. If the condition is met for checking $M_{eiP} \neq M_{ei}$, further calculation will proceed in block 32. In this block, the throttle position is calculated, i.e., the throttle opening angle φ_{tr}, accounting for changes in the throttle opening angle $\Delta\varphi_{tr}$, i.e: $\varphi_{tri}=\varphi_{tri} \pm \Delta\varphi_{tr}$. If the condition $M_{eiP} \neq M_{ei}$ is met, the calculation is performed in block 17. Block 18 determines the amount of heat transferred from the working fluid in the engine cylinder to the cooling system coolant under the duty cycle Q_{Tc}, considering the heat values. It is transferred specifically from the working fluid in the vehicle engine cylinder to the main coolant of the engine cooling system for the *j*-th interval of the duty cycle $dQ_{Tj}: Q_{Tic}=\sum j=1^n dQ_{Tj}$, J. And also the temperature of the exhaust gases in the engine exhaust pipe (receiver) $t_{EGi}=f(n_{ei}, M_{ei}, T_0)$, K. When using a thermal readiness system [7, 10, 48] based on a thermal storage device – phase-change thermal accumulator, the amount of heat is adjusted in block 20. It is transferred from the fuel assembly to the cooling system by the amount of coolant heating from the elements of the thermal readiness system. This occurs in the modes of engine pre-start and post-start warm-up for a vehicle capable of running on petrol and LPG. The accumulated heat in the heat storage device – phase-change thermal accumulator of the thermal readiness system [33–36, 48] is also taken into account (block 21).

Block 21 calculates the parameters of the discharge cycle of the heat storage device – phase-change thermal accumulator of the thermal readiness system. The operation of the phase-change thermal accumulator in the discharge mode is the inverse function of the charging process calculation. The transfer process of thermal energy stored by the heat storage material to the transport fluid – engine coolant is the process of heat transfer from one medium to another via a heat exchanger. The calculation primarily involves determining the heat transfer coefficient K_{TA}. The thermal energy received by the coolant from the phase-change thermal accumulator per unit time can be described by equation [7, 10, 33]:

$$q_{TA} = K_{TA} \cdot dT_{TA} \cdot F_{TA}, \mathrm{W}, \tag{5}$$

where dT_{TA} is the average temperature head, K; F_{TA} is the heat exchange area, m^2.

The average temperature head is also calculated in block 21:

$$dT_{TA} = \frac{\left(T_{HSM1} - T_{W1}\right) - \left(T_{HSM2} - T_{W2}\right)}{In\dfrac{\left(T_{HSM1} - T_{W1}\right)}{T_{HSM2} - T_{W2}}}, \tag{6}$$

where T_{HSM1}, T_{HSM2} are the initial and final heating temperatures of the heat storage material; T_{W1}, T_{W2} are the initial and final temperatures of the cooling system coolant (in engine operation – depending on fuel type).

In addition, the heat transfer coefficient K_{TA} is determined by the following relationship:

$$K_{TA} = \frac{1}{\dfrac{1}{\alpha_{TA}} + \dfrac{\delta}{\lambda} + \dfrac{1}{\alpha_W}}, \frac{\mathrm{W}}{\mathrm{m^2 K}}, \tag{7}$$

where α_{TA} is the heat transfer coefficient from the wall to the heat storage material, $W/(m^2 \cdot K)$; λ is the thermal conductivity of the heat exchanger tube material, $W/(m^2 \cdot K)$; Δ is the wall thickness, m; α_W is the heat transfer coefficient from the coolant to the wall, $W/(m^2 \cdot K)$.

The heat transfer coefficient from the test wall to the heat storage material:

$$\alpha_{TA} = \frac{2\lambda_{HSM}}{d_{out} In \dfrac{dx}{d_{out}}}, \tag{8}$$

where λ_{HSM} is the thermal conductivity of the heat storage material, d_{out} is the outer diameter of the heat exchanger tubes, dx is the phase-change zone.

The heat transfer coefficient from the coolant (liquid) to the wall:

$$\alpha_W = \frac{Nu_W \cdot \lambda_W}{d_{in}}, \tag{9}$$

where λ_W is the kinetic density of the fluid, m^2/s; Nu_w is the Nusselt number; d_{in} is the inner diameter of the heat exchanger tube of the thermal accumulator.

The thermal energy released by the heat storage device – phase-change thermal accumulator during the discharge process consists of the thermal energy of cooling the heat storage material and the thermal energy of the phase change itself. The discharge time of the phase-change thermal accumulator depends on the flow rate of the coolant discharging the phase-change thermal accumulator. In block 19, the hourly fuel consumption $G_{fuel,i}$, kg/h, and the hourly air consumption $G_{air,i}$, kg/h, of the engine converted to run on petrol and LPG are determined. Further, in block 28, the calculation of the hourly exhaust gas output, G_{EGi}, kg/h, coolant temperature $t_{Bi+1}=f(t_{Bi}, Q_{Tic})$, K, and catalytic converter temperature $t_{Hi}=f(G_{EGi}, n_{ei}, t_{EGi})$, K, is performed, as calculated in block 25.

The environmental performance of a vehicle engine capable of running on petrol and LPG is calculated in blocks 29–31. Block 29 calculates the concentrations of CO (%), C_mH_n (ppm) and NO_x (ppm) before the catalytic converter: $(E_{CO_i}, E_{C_mH_{ni}}, E_{NO_{xi}}) = f(n_{ei}, M_{ei}, \alpha_i)$. In block 30, the neutralization efficiency of substances is determined: CO, C_mH_n, NO_x, %, which is exactly the following: $(E_{CO_i}, E_{C_mH_{ni}}, E_{NO_{xi}}) = f(\alpha_i, t_{H_i})$. In addition, in block 30 of the algorithm, the concentrations of CO (%), NO_x (ppm), C_mH_n (ppm) are determined after the catalytic converter unit. These are the following dependencies:

$$\begin{aligned}&\left(\mathrm{CO}_{iH}, \mathrm{C}_m\mathrm{H}_{ni}, \mathrm{NO}_{xi}\right) = \\ &= \left(\mathrm{CO}_i, \mathrm{C}_m\mathrm{H}_{ni}, \mathrm{NO}_{xi}\right)\left(E_{\mathrm{CO}_i}, E_{\mathrm{C}_m\mathrm{H}_{ni}}, E_{\mathrm{NO}_{xi}}\right)/100.\end{aligned}$$

Block 31 defines mass emissions: CO, C_mH_n, NO_x, (kg/h). The functionality can be represented by the following dependency:

$$\left(G_{\mathrm{CO}}, G_{\mathrm{C}_m\mathrm{H}_{ni}}, G_{\mathrm{NO}_{xi}}\right) = f\left(\alpha_i, G_{fuel,i}, G_{air,i}; \mathrm{CO}_i^H, \mathrm{C}_m\mathrm{H}_{ni}^H, \mathrm{NO}_{xi}^H\right).$$

After calculating engine fuel consumption and exhaust gas emissions of in block 32, the calculation cycle number is changed to the next one. It is the sequence number of the calculation step that is changed, i, $i=i+1$. In block 33, the current time since the engine start-up is changed: $\tau_i=\tau_{i-1}+120/n_{ei-1}$. The improvement of the algorithm of the mathematical model for engine fuel consumption and exhaust gas emissions is shown in Fig. 3 in blocks 1, 2, 3, 5, 6. It includes the integration of additional components for gas equipment and the thermal readiness system in the vehicle study algorithm, accommodating the dual-fuel capability (petrol and LPG). Blocks 20, 21 check the performance of the phase-change thermal accumulator. In block 22, the temperature of the engine cooling system is monitored within $T_C \geq 50$ °C. If the cooling system temperature exceeds 50 °C, the engine runs on LPG; otherwise, on petrol. Liquid fuel and hourly air consumption $G_{fuel,i}$, $G_{air,i}$ are determined in block 23. In block 24, hourly gas fuel (LPG) and air consumption $G_{fuel,i}$, $G_{air,i}$ are determined. After that, in block 27, the fuel consumption coefficients for liquid fuel (petrol), $K_{GTP.P.}$, and LPG, $K_{GTG.P.}$, without thermal preparation and for liquid fuel after using the thermal preparation system as part of the TA, $K_{GTP.P.}$ TA, are determined using the appropriate formulas. To ensure the performance of the PTA, block 20 monitors and checks the TA temperature within the range set by the operating technology and design, the minimum accumulated heat temperature $T_{TA} \geq 135$ °C and the maximum temperature – $T_{TA} \leq 150$ °C. If the temperature of the thermal accumulator of the thermal readiness system does not reach 150 °C, a signal is sent to block 33. It changes the current time since the engine start-up: $\tau_i=\tau_{i-1}+120/n_{ei-1}$, and a command is sent to block 34. The temperature of the engine cooling system is monitored there within $T_C \geq 85$ °C. If the cooling system temperature reaches 85 °C, the engine is switched off, indicating that the heat storage device – thermal accumulator has been charged and its temperature is within the range $T_{TA} \geq 135$ °C, $T_{TA} \leq 150$ °C. However, if the temperature of the engine cooling system has not reached $T_C \geq 85$ °C, the engine continues to operate in minimum idle mode until the phase-change thermal accumulator is charged and the accumulated thermal energy reaches $Q_{TA}=47.25$ kJ/K, which is monitored in block 21.

5. 4. Features of the program for calculating and studying fuel consumption and harmful emissions of vehicle engines

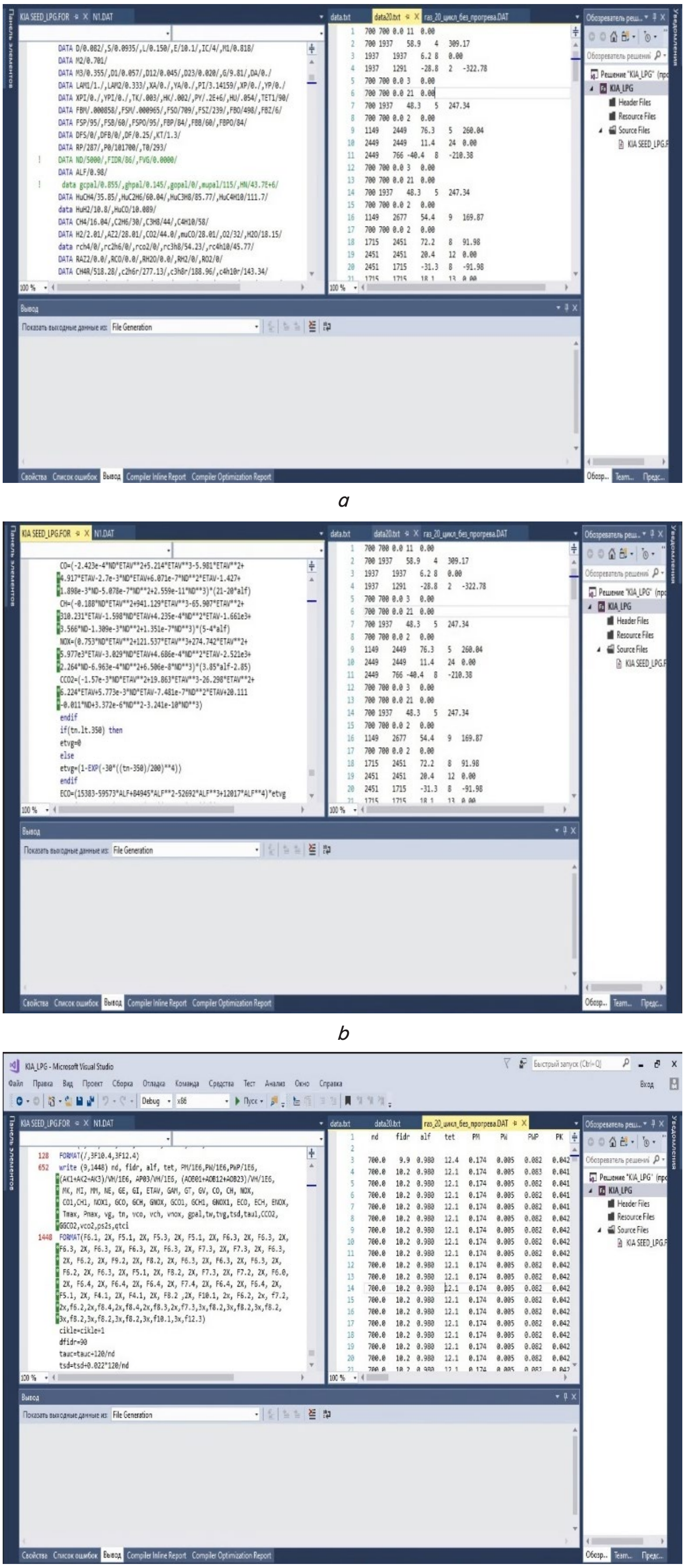
By implementing the improved algorithm in the mathematical model, dependencies were obtained for the engine warm-up temperature, fuel consumption, and exhaust gas emissions [61, 62]. The dependencies were derived for the driving cycle and thermal readiness processes in the corresponding modes [61, 62]. Fragments of the input data program listing, calculation program listing, and calculation results listing based on the programming results for the KIA CEE'D 2.0 5MT2 vehicle are shown in Fig. 4.

The improved algorithm of the research program and the enhanced mathematical model (Fig. 3, 4) enable the evaluation of engine operation in terms of fuel consumption and emissions. The engine is capable of running on petrol and LPG and is equipped with a thermal readiness system.

The analysis focused on the obtained values and indicators for both current and total fuel consumption, as well as exhaust gas emissions of vehicle engines under established operational modes. The modes included pre-start thermal preparation, post-start warm-up, driving within a standard cycle, and route-specific driving conditions. Fuel consumption in the driving cycle was calculated for a KIA CEE'D 2.0 5MT2 vehicle equipped with a G4GC engine adapted for operation on petrol and LPG, and fitted with a thermal readiness system. Using a similar methodology and the enhanced model, dependencies for vehicle movement modes during warm-up while driving were derived.

The adequacy of the experimental and calculated (including graphical) dependencies was evaluated using several statistical indicators: maximum absolute deviation, standard deviation, and multiple correlation coefficients determined by Fisher's criterion [61, 62]. This evaluation accounted for fuel consumption and exhaust emissions of a vehicle engine operating on both petrol and LPG. The results confirmed that the derived dependencies accurately describe the engine as a fuel and air consumer, as well as a source of exhaust gas emissions [61, 62].

Adequacy was further validated by assessing reproducibility, consistency, and homogeneity of variance. During the assessment, both stationary and dynamic vehicle characteristics were examined.



a

```
      DATA D/0.082/,S/0.0935/,L/0.150/,E/10.1/,IC/4/,M1/0.818/
      DATA M2/0.701/
      DATA M3/0.355/,D1/0.057/,D12/0.045/,D23/0.020/,G/9.81/,DA/0./
      DATA LAM1/1./,LAM2/0.333/,XA/0./,YA/0./,PI/3.14159/,XP/0./,YP/0./
      DATA XPI/0./,YPI/0./,TK/.003/,HK/.002/,PY/.2E+6/,HU/.054/,TET1/90/
      DATA FBM/.000858/,FSM/.000965/,FSO/709/,FSZ/239/,FBO/498/,FBZ/6/
      DATA FSP/95/,FSB/60/,FSPO/95/,FBP/84/,FBB/60/,FBPO/84/
      DATA DFS/0/,DFB/0/,DF/0.25/,KT/1.3/
      DATA RP/287/,P0/101700/,T0/293/
!     DATA ND/5000/,FIDR/86/,FVG/0.0000/
      DATA ALF/0.98/
!      data gcpal/0.855/,ghpal/0.145/,gopal/0/,mupal/115/,HN/43.7E+6/
      DATA HuCH4/35.85/,HuC2H6/60.04/,HuC3H8/85.77/,HuC4H10/111.7/
      data HuH2/10.8/,HuCO/10.089/
      DATA CH4/16.04/,C2H6/30/,C3H8/44/,C4H10/58/
      DATA H2/2.01/,AZ2/28.01/,CO2/44.0/,muCO/28.01/,O2/32/,H2O/18.15/
      data rch4/0/,rc2h6/0/,rco2/0/,rc3h8/54.23/,rc4h10/45.77/
      DATA RAZ2/0.0/,RCO/0.0/,RH2O/0.0/,RH2/0/,RO2/0/
      DATA CH4R/518.28/,c2h6r/277.13/,c3h8r/188.96/,c4h10r/143.34/
```

```
700 700 0.0 11  0.00
700 1937    58.9    4   309.17
1937    1937    6.2 8   0.00
1937    1291    -28.8   2   -322.78
700 700 0.0 3   0.00
700 700 0.0 21  0.00
700 1937    48.3    5   247.34
700 700 0.0 2   0.00
1149    2449    76.3    5   260.04
2449    2449    11.4    24  0.00
2449    766 -40.4   8   -210.38
700 700 0.0 3   0.00
700 700 0.0 21  0.00
700 1937    48.3    5   247.34
700 700 0.0 2   0.00
1149    2677    54.4    9   169.87
700 700 0.0 2   0.00
1715    2451    72.2    8   91.98
2451    2451    20.4    12  0.00
2451    1715    -31.3   8   -91.98
1715    1715    18.1    13  0.00
```

b

```
      CO=(-2.423e-4*ND*ETAV**2+5.214*ETAV**3-5.981*ETAV**2+
     *4.917*ETAV-2.7e-3*ND*ETAV+6.071e-7*ND**2*ETAV-1.427+
     *1.898e-3*ND-5.078e-7*ND**2+2.559e-11*ND**3)*(21-20*alf)
      CH=(-0.188*ND*ETAV**2+941.129*ETAV**3-65.907*ETAV**2+
     *310.231*ETAV-1.598*ND*ETAV+4.235e-4*ND**2*ETAV-1.661e3+
     *3.566*ND-1.309e-3*ND**2+1.351e-7*ND**3)*(5-4*alf)
      NOX=(0.753*ND*ETAV**2+121.537*ETAV**3+274.742*ETAV**2+
     *5.977e3*ETAV-3.029*ND*ETAV+4.686e-4*ND**2*ETAV-2.521e3+
     *2.264*ND-6.963e-4*ND**2+6.506e-8*ND**3)*(3.85*alf-2.85)
      CCO2=(-1.57e-3*ND*ETAV**2+19.863*ETAV**3-26.298*ETAV**2+
     *6.224*ETAV+5.773e-3*ND*ETAV-7.481e-7*ND**2*ETAV+20.111
     *-0.011*ND+3.372e-6*ND**2-3.241e-10*ND**3)
      endif
      if(tn.lt.350) then
      etvg=0
      else
      etvg=(1-EXP(-30*((tn-350)/200)**4))
      endif
      ECO=(15383-59573*ALF+84945*ALF**2-52692*ALF**3+12017*ALF**4)*etvg
```

```
700 700 0.0 11  0.00
700 1937    58.9    4   309.17
1937    1937    6.2 8   0.00
1937    1291    -28.8   2   -322.78
700 700 0.0 3   0.00
700 700 0.0 21  0.00
700 1937    48.3    5   247.34
700 700 0.0 2   0.00
1149    2449    76.3    5   260.04
2449    2449    11.4    24  0.00
2449    766 -40.4   8   -210.38
700 700 0.0 3   0.00
700 700 0.0 21  0.00
700 1937    48.3    5   247.34
700 700 0.0 2   0.00
1149    2677    54.4    9   169.87
700 700 0.0 2   0.00
1715    2451    72.2    8   91.98
2451    2451    20.4    12  0.00
2451    1715    -31.3   8   -91.98
1715    1715    18.1    13  0.00
```

c

```
  128 FORMAT(/,3F10.4,3F12.4)
  652 write (9,1448) nd, fidr, alf, tet, PM/1E6,PW/1E6,PWP/1E6,
     *(AK1+AK2+AK3)/VH/1E6, AP03/VH/1E6, (AOB01+AOB12+AOB23)/VH/1E6,
     * MK, MI, MM, NE, GE, GI, ETAV, GAM, GT, GV, CO, CH, NOX,
     * CO1,CH1, NOX1, GCO, GCH, GNOX, GCO1, GCH1, GNOX1, ECO, ECH, ENOX,
     * Tmax, Pmax, vg, tn, vco, vch, vnox, gpal,tw,tvg,tsd,tau1,CCO2,
     *GGCO2,vco2,ps2s,qtci
 1448 FORMAT(F6.1, 2X, F5.1, 2X, F5.3, 2X, F5.1, 2X, F6.3, 2X, F6.3, 2X,
     *F6.3, 2X, F6.3, 2X, F6.3, 2X, F6.3, 2X, F7.3, 2X, F7.3, 2X, F6.3,
     * 2X, F6.2, 2X, F9.2, 2X, F8.2, 2X, F6.3, 2X, F6.3, 2X, F6.3, 2X,
     * F6.2, 2X, F6.3, 2X, F5.1, 2X, F8.2, 2X, F7.3, 2X, F7.2, 2X, F6.0,
     * 2X, F6.4, 2X, F6.4, 2X, F6.4, 2X, F7.4, 2X, F6.4, 2X, F6.4, 2X,
     *F5.1, 2X, F4.1, 2X, F4.1, 2X, F8.2 ,2X, F10.1, 2x, F6.2, 2x, f7.2,
     *2x,f6.2,2x,f8.4,2x,f8.4,2x,f8.3,2x,f7.3,3x,f8.2,3x,f8.2,3x,f8.2,
     *3x,f8.2,3x,f8.2,3x,f8.2,3x,f10.1,3x,f12.3)
      cikle=cikle+1
      dfidr=90
      tauc=tauc+120/nd
      tsd=tsd+0.022*120/nd
```

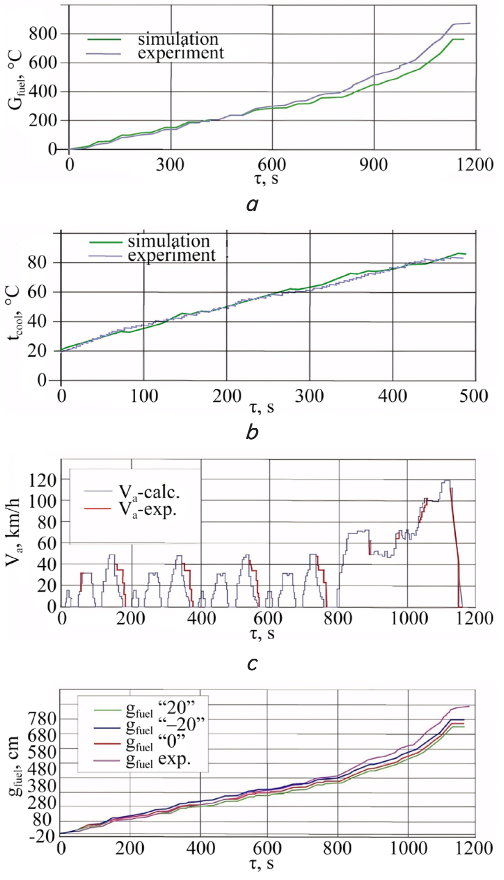
```
  nd      fidr   alf    tet     PM      PW      PWP     PK

 700.0    9.9  0.980   12.4   0.174   0.005   0.082   0.042
 700.0   10.2  0.980   12.1   0.174   0.005   0.083   0.041
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.041
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.041
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.041
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.042
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.042
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.042
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.042
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.042
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.042
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.042
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.042
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.042
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.042
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.042
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.042
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.042
 700.0   10.2  0.980   12.1   0.174   0.005   0.082   0.042
```

Fig. 4. Program listing: *a* – fragment of the input data listing; *b* – fragment of the calculation program listing; *c* – fragment of the calculation results listing

These included exhaust gas emissions, fuel consumption during thermal preparation, thermal preparation time, engine temperature dynamics, speed variations, and others (Fig. 5). The comparison of experimental and calculated data on fuel consumption and engine temperature during operation (Fig. 5) confirmed the adequacy of the mathematical models used in the study.

The analysis specifically evaluated a vehicle engine converted to operate on petrol and LPG, equipped with a thermal readiness system, under the modes defined by the European Urban Driving Cycle. This comparison validated the model's capability to reflect real-world vehicle behavior under diverse thermal preparation and operational scenarios.



a

b

c

d

Fig. 5. Results of adequacy validation of performance modeling for a vehicle engine converted to run on petrol and LPG under the European Urban Driving Cycle modes: *a* — exhaust gas emissions; *b* — engine temperature dynamics; *c* — speed variations in the driving cycle; *d* — fuel consumption during thermal preparation

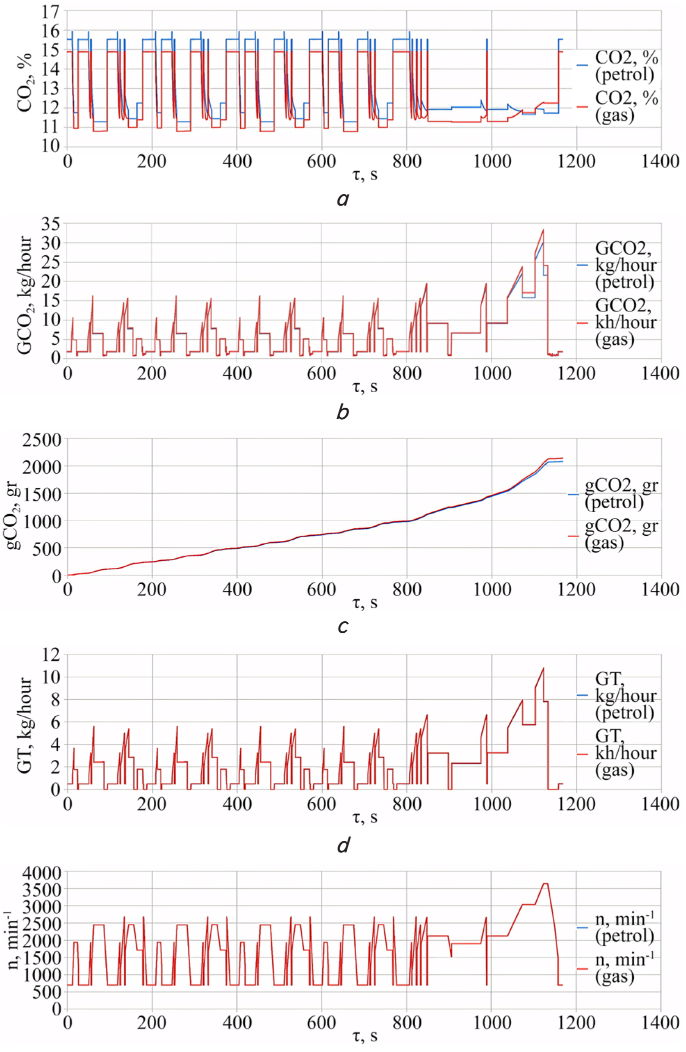
Experimental data were obtained by vehicle testing in driving modes approximating the studied European Urban Driving Cycle [17, 18]. For evaluating the thermal preparation (readiness) periods, the maximum deviation of the calculated data from the experimental results was as follows: fuel consumption 4.49 %, coolant temperature 5.19 %.

5. 5. Some results of using the developed mathematical model and its implementation possibilities

Fig. 6–8 present excerpts from the simulated European Urban Driving Cycle for the KIA CEE'D 2.0 5MT2 vehicle, equipped with the G4GC engine (4FS 8.2/9.35) capable of running on both petrol and LPG. The vehicle is also fitted with a phase-change thermal accumulator integrated into its cooling system. Some discrepancies between the calculated and experimental fuel consumption data are attributed to differences between the modeled conditions and the actual atmospheric and road conditions during testing.

The study evaluated the impact of thermal preparation on engine fuel consumption and exhaust gas emissions. This evaluation was based on ensuring sufficient modeling adequacy. The observed deviations were within acceptable limits, allowing for a reliable comparative analysis of the results. The adequacy of the mathematical model dependencies was verified, as shown in Fig. 5. The verification confirmed that the mathematical model sufficiently describes the processes within the studied system.

This validation enables the use of the improved mathematical model for theoretical investigations of an engine's thermal preparation system (TPS) during pre- and post-start stages. The model accounts for the specifics of using different fuel types, ensuring its applicability to diverse operational scenarios.



a

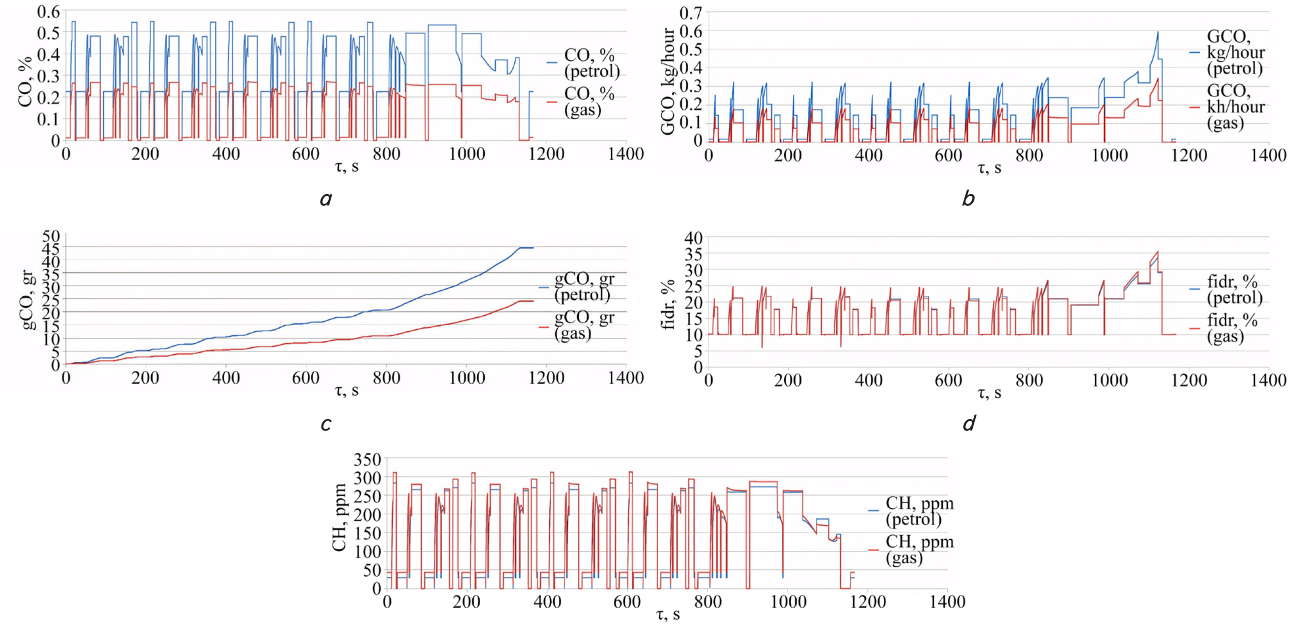
b

c

d

e

Fig. 6. Results of the calculation study on the modeled European Urban Driving Cycle for the KIA CEE'D 2.0 5MT2 vehicle converted to run on petrol and LPG: *a* — CO_2 concentration before the catalytic converter; *b* — mass CO_2 emissions after the catalytic converter; *c* — total CO_2 emissions per driving cycle; *d* — fuel consumption per driving cycle; *e* — engine speed

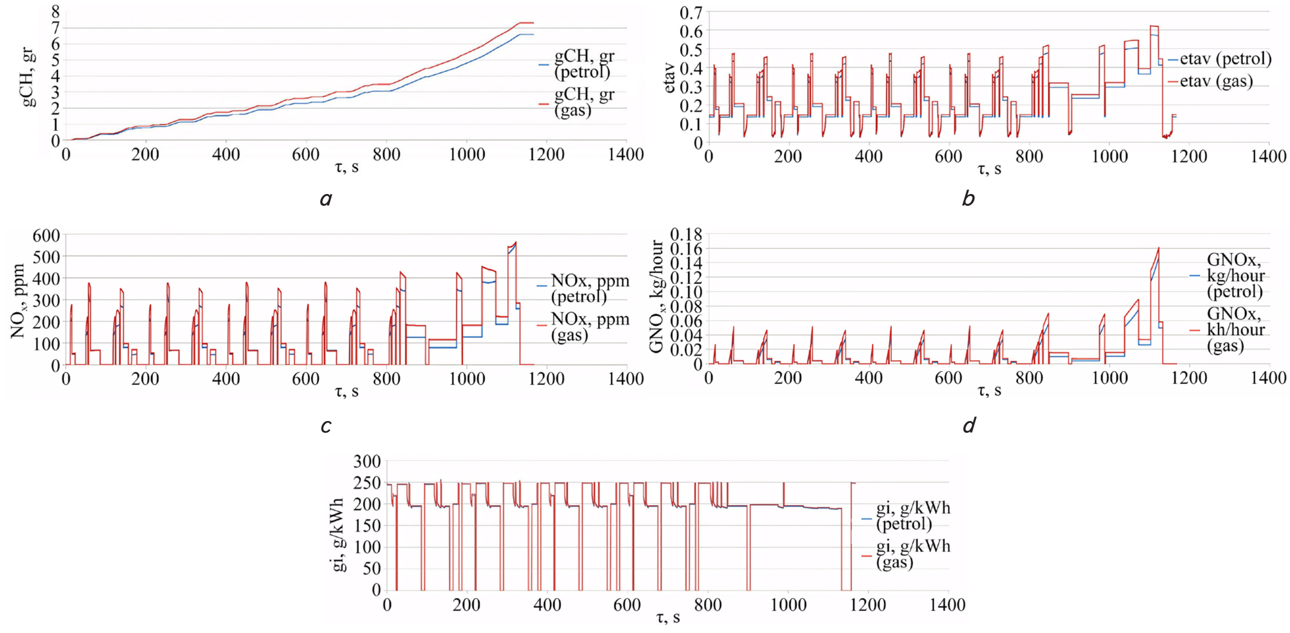


a *b*

c *d*

e

Fig. 7. Results of the calculation study on the modeled European Urban Driving Cycle of the KIA CEE'D 2.0 5MT2 vehicle converted to run on petrol and LPG: *a* – CO concentration; *b* – mass CO emissions; *c* – total CO emissions per driving cycle; *d* – throttle position; *e* – CH concentration



a *b*

c *d*

e

Fig. 8. Results of the calculation study on the modeled European Urban Driving Cycle of the KIA CEE'D 2.0 5MT2 vehicle converted to run on petrol and LPG: *a* – mass CH emissions; *b* – volumetric efficiency; *c* – total NO_x emissions per driving cycle; *d* – mass NO_x emissions; *e* – indicator fuel consumption

The application of the developed approach, algorithm and mathematical model for studying the thermal preparation of a vehicle engine ensures the comprehensive practical implementation of the proposed approach. The implementation possibilities of the approach to ensuring vehicle thermal preparation processes by fuel consumption and exhaust gas emissions are shown in Table 3. This primarily involves (as shown in Fig. 2) monitoring of parameters and measurement of technical condition indicators of the vehicle. Secondly, this encompasses the potential for analytical research to derive parameters and indicators of thermal preparation, fuel consumption, and emissions of a vehicle engine based on the developed and adapted mathematical model. The results take into account the specific operational features of an engine capable of running on both petrol and LPG.

Table 3

Implementation possibilities of the approach to ensuring vehicle thermal preparation processes by fuel consumption and exhaust gas emissions

Vehicle thermal readiness modes for a petrol or LPG engine equipped with a thermal preparation system based on a phase-change thermal accumulator/ Mode No.	Components of the study of fuel consumption and emissions of a vehicle engine capable of operating on petrol and LPG under operating conditions equipped with a thermal preparation system based on a phase-change thermal accumulator								
	Monitoring vehicle parameters for an engine capable of running on petrol and LPG under operating conditions			Measurement of vehicle parameters and technical condition indicators for an engine capable of running on petrol and LPG under operating conditions			Analytical study to obtain parameters and indicators of thermal preparation, fuel consumption and emissions of a vehicle engine capable of running on petrol and LPG, based on the adapted model		
	Defining parameters and indicators								
	fuel consumption	thermal preparation	emissions	fuel consumption	thermal preparation	emissions	fuel consumption	thermal preparation	emissions
Thermal readiness of a stationary vehicle with the engine running at minimum idle									
1	–	+	–	–	+	–	+	+	+
Thermal readiness of a stationary vehicle with the engine running at minimum idle, with electrical consumers and interior heating exchanger engaged									
2	–	+	–	–	+	–	+	+	+
Thermal readiness of a stationary vehicle with the engine running at minimum idle and in motion									
3	–/+	+	–/+	–/+	+	–/+	+	+	+
Thermal readiness of a vehicle in motion									
4	+	+	+	–/+	+	–/+	+	+	+

Notes: "–" – not possible, limitedly possible, not fully possible; "+"– possible; "–/+"– not possible/possible – only for specific processes.

6. Discussion of the results on the development of an approach to building an adapted model for ensuring the thermal readiness processes of a vehicle

An improved approach to developing an adapted model for ensuring the thermal readiness of a vehicle, with a focus on fuel consumption and exhaust gas emissions, is proposed. This approach is based on a systematic integration of the standard engine control system with components of a remote monitoring system for thermal readiness processes (Fig. 1). It incorporates the specifics of thermal readiness processes, including the operation of a thermal preparation system based on a phase-change thermal accumulator (Fig. 2) and the design characteristics of a vehicle engine capable of operating on both petrol and LPG [17, 18].

The approach also emphasizes the importance of obtaining information through remote monitoring of vehicle and engine parameters (Fig. 1, 2).

Direct measurement and remote transmission of the engine's thermal state parameters using additional integrated sensors.

It is also supported by the results of an analytical study using an adapted model tailored to the vehicle's operating conditions and fuel type. This model is designed to derive parameters and indicators of thermal preparation, fuel consumption, and emissions (Table 7).

The study confirms that applying mathematical modeling in the analysis of engine thermal preparation processes enables tracking changes in fuel consumption and emissions during start-up. These parameters cannot be fully captured through direct measurement or monitoring under real operating conditions (Fig. 2). However, modeling ensures the required accuracy in calculations and forecasting while maintaining simplicity and low operational costs. This is achieved by correlating the necessary thermal preparation parameters with the key performance indicators of the vehicle and engine under relevant operating conditions.

Furthermore, the proposed approach addresses the limitations of existing methods, including those relying solely on vehicle operation monitoring or experimental measurement of technical condition parameters during research processes [17, 18]. The approach combines the strengths of these methods while mitigating their weaknesses.

The algorithm and mathematical model for the system [18, 33–36, 48] are grounded in methodologies for assessing vehicle performance to achieve the study's objectives. The investigation was conducted on vehicles capable of running on petrol and LPG under the following conditions: various modes of the New European Driving Cycle (NEDC); various modes of the European Urban Driving Cycle, in accordance with UNECE Regulations 83–05 [33–36, 48, 57]; various thermal preparation modes of the experimental vehicle (Fig. 2), including warm-up while stationary, in motion, and on designated routes [23, 58–60].

To refine the algorithm and mathematical model for warm-up processes, equations ((2)–(9)) are provided in line with the provisions illustrated in Fig. 3. These refinements aim to enhance the model's accuracy and applicability for studying vehicle thermal readiness and fuel efficiency under diverse conditions.

The key feature of the proposed algorithm and its implementation for analytical and computational studies is the parallel use of two interdependent models. These models are designed to work in tandem: the "Petrol engine-neutralizer" mathematical model and the "Gas engine-neutralizer" (LPG) mathematical model [33–36, 48]. Upon exiting the "Engine-neutralizer" model, further calculations proceed in three directions: determining the energy, fuel efficiency, and environmental performance of a vehicle engine adapted to run on petrol and LPG. The modeling of internal combustion engine (ICE) workflows is based on the volume balance method [10, 38, 39], enabling simultaneous consideration and comparison of engine system states and performance on petrol and LPG during thermal preparation with a phase-change thermal accumulator.

The model's constraints, set during the implementation of the improved algorithm, can be adjusted to accommodate variations in heat storage design, heat storage materials, thermal preparation cycles, and other factors. These adjustments allow the model to be tailored to different research objectives or vehicle operating conditions. The approach proposed in the study requires accounting for these limitations to generate new and relevant thermal preparation data.

A noted drawback of the proposed approach is its reliance on prior bench test results of the vehicle and its engine, as well as operational monitoring data. Additionally, the formalization process and outcomes are significantly influenced by the researchers' expertise level. However, these challenges can be mitigated through adopting a structured formalization of vehicle thermal preparation states based on thermal preparation cycles.

The algorithm's scope can be broadened through the inclusion of test data libraries for vehicles under various operating conditions. This would facilitate the study of all proposed thermal preparation modes, as well as standardized vehicle testing modes. Unlike earlier models, the proposed algorithm and program allow for the integration of experimental test databases, vehicle monitoring data, and similar datasets into the research process. Furthermore, this model enables the analysis of operating modes and conditions that are otherwise inaccessible through experimental methods (Table 3).

The model's adequacy under accepted conditions (Fig. 5) was verified through reproducibility, consistency, and homogeneity of variance tests. During the verification process, specific characteristics of a stationary vehicle and during operation were evaluated, including: exhaust gas emissions, fuel consumption during thermal preparation, thermal preparation time, engine temperature dynamics, speed variations, and others. The comparison of experimental and calculated data on fuel consumption and engine temperature (Fig. 5) confirmed the mathematical model's accuracy in representing vehicle operation. The engine, converted to run on petrol and LPG and equipped with a thermal preparation system (TPS), was evaluated under the European Urban Driving Cycle modes. Experimental data were obtained by vehicle testing under conditions approximating the European Urban Driving Cycle [17, 18].

To specifically assess thermal preparation periods, the maximum deviations between calculated and experimental data were as follows: fuel consumption, 4.49 %; coolant temperature, 5.19 %. These results demonstrate the model's capability to provide accurate and reliable predictions under the studied conditions.

Well-established studies [31–36, 48] detail various methods for analyzing internal combustion engines. However, the model developed in this study, along with the improved algorithm, offers greater unification in its approach and provides more detailed insights into the constituent processes and modes. This model broadens the scope of engine research, particularly for thermal preparation processes, covering both pre-start and post-start stages across different fuel types.

A key advantage of the proposed approach, algorithm, and model is their applicability to comprehensive engine studies under real-world conditions using monitoring tools. Additionally, the model's ability to analyze pre-start thermal preparation using a thermal preparation system based on a phase-change thermal accumulator, when the engine is not running, is a significant breakthrough. This capability is unattainable with the models and methodologies described in [31–36, 48].

The model's limitation is its reliance on a substantial experimental database and dependence on the specific design features of the thermal preparation system and the thermal accumulator. However, this is not a critical constraint for preliminary aggregate studies.

One drawback of the model is the need to revise all its components when new elements or thermal preparation modes are introduced. Nevertheless, this issue can be mitigated by leveraging system automation techniques for programming complex systems.

The model's future development could involve creating an automated research system based on its framework. This system could feature automated integration with vehicle monitoring databases and experimental data from direct measurements. Such advancements would significantly expand the model's applicability, enhance its functionality, and improve the efficiency and accuracy of research results.

7. Conclusions

1. The paper substantiates the application of an adapted model for ensuring the thermal readiness processes of a vehicle and conducting experimental and computational-analytical studies to implement this approach. This enables consideration of the specifics of engine operation during pre- and post-start warm-up using a thermal preparation system. The model accounts for fuel types, design features of the thermal preparation system, engine operating modes, and ambient temperature. This approach and model adaptation improve the evaluation accuracy of fuel consumption and exhaust gas emissions of engines under real-world operating conditions.

2. A comprehensive thermal preparation cycle has been developed to guide the organization of pre- and post-start warm-up of the engine and vehicle. The cycle incorporates rational warm-up modes for an engine converted to run on petrol and LPG and equipped with a thermal preparation system based on a phase-change thermal accumulator (TA). The cycle allows for an immediate switch from petrol to LPG after starting and load acceptance while selecting appropriate operation modes for the thermal preparation system (TPS). Four primary thermal preparation modes for engines capable of running on petrol and LPG have been established. These modes demonstrate the full potential of thermal readiness for ensuring efficient vehicle start-up. The ability to evaluate fuel consumption and emissions for such engines equipped with a thermal preparation system based on a phase-change thermal accumulator has been demonstrated. This enhances the assessment of fuel consumption and exhaust emissions across various thermal preparation modes.

3. The algorithm for calculating fuel consumption and emissions of vehicle engines converted to run on gas fuel under operating conditions has been refined. A key feature of the proposed algorithm is the parallel use of two interrelated models: the "Petrol engine-neutralizer" mathematical model and the "Gas engine-neutralizer" (LPG) mathematical model.

These models are adapted to work together seamlessly. Once the "Engine-neutralizer" model is exited, calculations proceed in three directions to determine the energy, fuel efficiency, and environmental performance of a vehicle engine adapted for petrol and LPG. This approach enables a detailed analysis of the engine's efficiency by evaluating current and total indicator values. The evaluation encompasses fuel consumption and emissions during pre- and post-start thermal preparation, as well as during the driving cycle and on specific routes.

4. The improved algorithm and mathematical model have provided dependencies for the warm-up temperature, fuel consumption, and exhaust gas emissions of a vehicle engine as functions of time. These dependencies were derived for driving cycle and thermal readiness processes under respective modes. Key fragments of the program and calculation results listing for the KIA CEE'D 2.0 5MT2 vehicle are presented. Verification of the model's adequacy revealed a maximum deviation of 4.49 % for fuel consumption and 5.19 % for coolant temperature during the thermal preparation period. These results confirm that the mathematical dependencies accurately describe the studied system processes, ensuring the model's reliability for theoretical and practical applications.

5. The results obtained enable theoretical research using an enhanced mathematical model of the engine's thermal preparation system (TPS) during pre- and post-start stages. This model accounts for the specifics of operating with different fuel types. The findings are validated by deriving the corresponding dependencies of exhaust gas emissions for both petrol and LPG operation, as demonstrated through the modeled European Urban Driving Cycle. A calculation framework has been developed for assessing fuel consumption and environmental performance of vehicles running on petrol and LPG. This framework systematically integrates methods and tools for acquiring operational data. Information is collected through remote monitoring of the vehicle's technical condition parameters, experimental studies of the TPS, and analytical calculations based on the combined data from these sources. This comprehensive approach ensures accurate and reliable evaluations of vehicle performance across different fuels and operating conditions.

Conflict of interest

The authors declare no conflict of interest related to this research, whether financial, personal, authorship, or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used in the creation of this work.

References

1. Hutarevych, Yu. F., Zerkalov, D. V., Hovorun, A. H., Korpach, A. O., Merzhyievska, L. P. (2006). Ekolohiya ta avtomobilnyi transport. Kyiv: Aristei, 292.
2. Komov, P. B., Volkov, V. V. (2005). Problemy orhanizatsiyi tekhnichnoi ekspluatatsiyi avtomobiliv u suchasnykh umovakh hospodariuvannia. Visnyk Skhidnoukrainskoho natsionalnoho universytetu im. Volodymyra Dalia, 6 (88), 128–132.
3. Volkov, V. P., Kravchenko, A. P. (2008). Avtomobil': teoriya ekspluatacionnyh svoystv. Lugansk: Noulidzh, 300.
4. Turenko, A. N., Bogomolov, V. A., Abramchuk, F. I. et al. (2006). O trebovaniyah k konstrukcii i rabochemu processu pnevmodvigatelya dlya kombinirovannoy energoustanovki avtomobilya. Avtomobil'niy transport, 18, 7–12.
5. Gritsuk, I. V., Mateichyk, V., Aleksandrov, V., Prilepsky, Y., Panchenko, S., Kagramanian, A. et al. (2019). Features of Modeling Thermal Development Processes of the Vehicle Engine Based on Phase-Transitional Thermal Accumulators. SAE Technical Paper Series. https://doi.org/10.4271/2019-01-0906
6. Trifonov, D. M., Manko, I. V., Syrota, O. V. (2015). Doslidzhennia riznykh metodiv prohrivu dvyhuna z iskrovym zapaliuvanniam, z metoiu optymizatsiyi vytraty palyva. Systemy i środki transportu samochodowego. Seria: Transport. Rzeszów, 201–208.
7. Adrov, D. S. (2011). Matematychne modeliuvannia roboty systemy okholodzhennia dvyhuna vnutrishnoho zghorannia utylizatsiynoi ustanovky pry vyznachenni chasu prohrivu. Zbirnyk nauk. prats DonIZT UkrDAZT, 27, 105–112.
8. Sekret, R., Starzec, P., Kotowicz, J. (2023). Research on water–ice heat accumulator and analysis of its potential use as hybrid source heat pump for building heating. Energy and Buildings, 300, 113670. https://doi.org/10.1016/j.enbuild.2023.113670
9. Gutarevich, Yu. F., Trifonov, D. M., Syrota, O. V. (2017). Car ZAZ-1102 improvement in fuel efficiency and environmental performance in warm-up phase after engine cold start. Academic Journal Series: Industrial Machine Building, Civil Engineering, 1 (48), 19–25. https://doi.org/10.26906/znp.2017.48.766
10. Verbovskyi, V. (2019). Otsinka dotsilnosti zastosuvannia systemy teplovoi pidhotovky z vykorystanniam akumulovanoi enerhiyi dlia statsionarnoho hazovoho dvyhuna. Systemy i zasoby transportu. Problemy ekspluatatsiyi i diahnostyky. Kherson: KhDMA, 288–307.
11. Mytrofanov, O., Proskurin, A., Poznanskyi, A. (2018). Analysis of the piston engine operation on ethanol with the synthesis-gas additives. Eastern-European Journal of Enterprise Technologies, 4 (1 (94)), 14–19. https://doi.org/10.15587/1729-4061.2018.136380

12. Gritsuk, I. V., Volkov, V., Mateichyk, V., Grytsuk, Y., Nikitchenko, Y., Klets, D. et al. (2018). Information Model of V2I System of the Vehicle Technical Condition Remote Monitoring and Control in Operation Conditions. SAE Technical Paper Series. https://doi.org/10.4271/2018-01-0024
13. Zaharchuk, V., Gritsuk, I. V., Zaharchuk, O., Golovan, A., Korobka, S., Pylypiuk, L., Rudnichenko, N. (2018). The Choice of a Rational Type of Fuel for Technological Vehicles. SAE Technical Paper Series. https://doi.org/10.4271/2018-01-1759
14. Eroshchenkov, S. A., Puzyr', V. G., Zhalkin, D. S., Bocharov, V. M. (2008). Vybor racional'noy sistemy progreva teplovoznyh dizeley. Sb. nauch. trudov UkrDAZT, 96, 174–185.
15. Trifonov, D. M. (2016). Vplyv pidihrivu povitria na vpusku na palyvnu ekonomichnist ta ekolohichni pokaznyky suchasnoho dvyhuna z iskrovym zapaliuvanniam. Visnyk Natsionalnoho transportnoho universytetu. Seriya "Tekhnichni nauky", 2 (35), 227–233.
16. Morosuk, T., Morosuk, C., Bishliaga, S. (2003). Thermodynamic analysis of traditional and alternative heating systems for Ukraine. In: Advances in Energy Studies. Reconsidering the Importance of Energy, 381–388.
17. Gritsuk, I., Pohorletskyi, D., Mateichyk, V., Symonenko, R., Tsiuman, M., Volodarets, M. et al. (2020). Improving the Processes of Thermal Preparation of an Automobile Engine with Petrol and Gas Supply Systems (Vehicle Engine with Petrol and LPG Supplying Systems). SAE Technical Paper Series. https://doi.org/10.4271/2020-01-2031
18. Gritsuk, I., Pohorletskyi, D., Pohorletska, N., Volkov, V., Volodarets, M., Khudiakov, I. et al. (2024). Features of Assessing Fuel Efficiency and Environmental Performance of Vehicles in Thermal Preparation Processes. SAE Technical Paper Series, 1. https://doi.org/10.4271/2024-01-5088
19. Verbovskyi, V. S. (2014). Otsinka dotsilnosti provedennia peredpuskovoi i pisliapuskovoi pidhotovky hazovoho dvyhuna K-159 M2 za dopomohoiu kompleksnoi systemy peredpuskovoho prohrivu. Zbirnyk nauk. prats DonIZT UkrDAZT, 39, 93–99.
20. Mateichyk, V., Kostian, N., Smieszek, M., Gritsuk, I., Verbovskyi, V. (2023). Review of Methods for Evaluating the Energy Efficiency of Vehicles with Conventional and Alternative Power Plants. Energies, 16 (17), 6331. https://doi.org/10.3390/en16176331
21. Aký je rozdiel medzi CNG a LPG. Available at: https://www.cngslovensko.sk/cng-vs-lpg
22. KAS IR LPG? Available at: https://www.dacia.lv/lv/special-offers/about-LPG.html
23. Kesariiskyi, O. G., Marchenko, A., Gritsuk, I., Mateichyk, V., Pylyov, V., Kravchenko, S. (2021). Laser Interferometry to Investigate the Strain and Stress State of Details and Units of Heat Engines. SAE International Journal of Engines, 15 (4), 459–469. https://doi.org/10.4271/03-15-04-0023
24. Castiglione, T., Pizzonia, F., Bova, S. (2016). A Novel Cooling System Control Strategy for Internal Combustion Engines. SAE International Journal of Materials and Manufacturing, 9 (2), 294–302. https://doi.org/10.4271/2016-01-0226
25. Gritsuk, I., Volkov, V., Mateichyk, V., Gutarevych, Y., Tsiuman, M., Goridko, N. (2017). The Evaluation of Vehicle Fuel Consumption and Harmful Emission Using the Heating System in a Driving Cycle. SAE International Journal of Fuels and Lubricants, 10 (1), 236–248. https://doi.org/10.4271/2017-26-0364
26. Kahramanian, A. O., Onyshchenko, A. V. (2011). Vykorystannia akumuliatoriv teploty, yak alternatyvnoho dzherela enerhiyi pry prohrivi teplovoziv. Zaliznychnyi transport Ukrainy, 1, 49–51.
27. Smyrnov, Y., Borysiuk, D., Volobuyeva, T., Nastenko, M., Plakhtii, T. (2023). Model for devising and defining technical development projects of motor transport enterprises. Eastern-European Journal of Enterprise Technologies, 5 (3 (125)), 23–34. https://doi.org/10.15587/1729-4061.2023.289004
28. Podrigalo, M., Klets, D., Sergiyenko, O., Gritsuk, I. V., Soloviov, O., Tarasov, Y. et al. (2018). Improvement of the Assessment Methods for the Braking Dynamics with ABS Malfunction. SAE Technical Paper Series. https://doi.org/10.4271/2018-01-1881
29. Mikhalevich, M., Yarita, A., Leontiev, D., Gritsuk, I. V., Bogomolov, V., Klimenko, V., Saravas, V. (2019). Selection of Rational Parameters of Automated System of Robotic Transmission Clutch Control on the Basis of Simulation Modelling. SAE Technical Paper Series. https://doi.org/10.4271/2019-01-0029
30. Parsadanov, I., Marchenko, A., Tkachuk, M., Kravchenko, S., Polyvianchuk, A., Strokov, A. et al. (2020). Complex Assessment of Fuel Efficiency and Diesel Exhaust Toxicity. SAE Technical Paper Series. https://doi.org/10.4271/2020-01-2182
31. Kashkanov, V. A., Kashkanov, A. A., Kuzhel, V. P. (2020). Informatsiyni systemy i tekhnolohiyi na avtomobilnomu transporti. Vinnytsia, 104. Available at: http://pdf.lib.vntu.edu.ua/books/IRVC/Kashkanov_2020_104.pdf
32. Trifonov, D. M. (2016). Pidvyshchennia efektyvnosti neitralizatsiyi vidpratsovanykh haziv dvyhuna z iskrovym zapaliuvanniam v rezhymi prohrivu. Systemy i środki transportu samochodowego. Seria: Transport. Rzeszów, 195–202.
33. Tsiuman, M. P., Golubov, O. S. (2012). Methods of determining the mechanical losses of piston engine. Problems of Friction and Wear, 57, 100–107. Available at: http://nbuv.gov.ua/UJRN/Ptz_2012_57_10
34. Hutarevych, Yu. F., Mateichyk, V. P. (1997). Matematychna model rozrakhunku pokaznykiv avtomobilnoho benzynovoho dvyhuna za riznykh sposobiv rehuliuvannia potuzhnosti. Pratsi Zakhidnoho naukovoho tsentru TAU "Proektuvannia, vyrobnytstvo ta ekspluatatsiya avtotransportnykh zasobiv i poizdiv", 4, 22–25.
35. Mateichyk, V. P., Yanovskyi, V. V., Kozachuk, I. S. (2003). Perevirka adekvatnosti matematychnoi modeli robochoho protsesu hazovoho dvyhuna. Visnyk NTU i TAU, 7, 55–59.

36. Mateichyk, V. P., Tsiuman, M. P. (2010). Doslidzhennia vplyvu rehuliuvalnykh parametriv na palyvnu ekonomichnist i ekolohichni pokaznyky benzynovoho dvyhuna z systemoiu neitralizatsiyi vidpratsovanykh haziv. Naukovi notatky, 28, 331–335. Available at: http://nbuv.gov.ua/UJRN/Nn_2010_28_66
37. Paraffin. Available at: https://www.cniga.com.ua/index.files/parafin.htm
38. Diesel-RK is an engine simulation tool. Diesel-RK. Available at: https://diesel-rk.com/Eng/
39. Kuleshov, A., Grekhov, L. (2013). Multidimensional Optimization of DI Diesel Engine Process Using Multi-Zone Fuel Spray Combustion Model and Detailed Chemistry NOx Formation Model. SAE Technical Paper Series. https://doi.org/10.4271/2013-01-0882
40. Gritsuk, I. V., Aleksandrov, V., Panchenko, S., Kagramanian, A., Sobol, O., Sobolev, A., Varbanets, R. (2017). Features of Application Materials While Designing Phase Transition Heat Accumulators of Vehicle Engines. SAE Technical Paper Series. https://doi.org/10.4271/2017-01-5003
41. Aleksandrov, V. D. (2011). Kinetika zarodysheobrazovaniya i massovoy kristallizacii pereohlazhdennyh zhidkostey i amorfnyh sred. Doneck: Donbass, 580.
42. Volodarets, M., Gritsuk, I., Chygyryk, N., Belousov, E., Golovan, A., Volska, O. et al. (2019). Optimization of Vehicle Operating Conditions by Using Simulation Modeling Software. SAE Technical Paper Series. https://doi.org/10.4271/2019-01-0099
43. Hahanov, V., Gharibi, W., Litvinova, E., Chumachenko, S., Ziarmand, A., Englesi, I. et al. (2017). Cloud-Driven Traffic Monitoring and Control Based on Smart Virtual Infrastructure. SAE Technical Paper Series. https://doi.org/10.4271/2017-01-0092
44. Kukhtyk, N. O. (2018). Determination of fuel consumption and concentration of harmful substances for warming the engine of a car in conditions of low ambient temperatures. The Journal of Zhytomyr State Technological University. Series: Engineering, 2 (82), 88–93. https://doi.org/10.26642/tn-2018-2(82)-88-93
45. Valero, A. et al. (1999). Structural theory and thermoeconomic diagnosis. Proceedings of Conference ECOS'99. Tokyo, 368–379.
46. Ulrich, C., Frieske, B., Schmid, S. A., Friedrich, H. E. (2022). Monitoring and Forecasting of Key Functions and Technologies for Automated Driving. Forecasting, 4 (2), 477–500. https://doi.org/10.3390/forecast4020027
47. Gorobchenko, O., Fomin, O., Gritsuk, I., Saravas, V., Grytsuk, Y., Bulgakov, M. et al. (2018). Intelligent Locomotive Decision Support System Structure Development and Operation Quality Assessment. 2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS), 239–243. https://doi.org/10.1109/ieps.2018.8559487
48. Melnyk, O., Onishchenko, O., Onyshchenko, S., Voloshyn, A., Ocheretna, V. (2023). Comprehensive Study and Evaluation of Ship Energy Efficiency and Environmental Safety Management Measures. Studies in Systems, Decision and Control, 665–679. https://doi.org/10.1007/978-3-031-35088-7_38
49. Mateichyk, V., Saga, M., Smieszek, M., Tsiuman, M., Goridko, N., Gritsuk, I., Symonenko, R. (2020). Information and analytical system to monitor operating processes and environmental performance of vehicle propulsion systems. IOP Conference Series: Materials Science and Engineering, 776 (1), 012064. https://doi.org/10.1088/1757-899x/776/1/012064
50. Vychuzhanin, V., Rudnichenko, N., Shybaiev, D., Gritsuk, I., Boyko, V., Shybaieva, N. et al. (2018). Cognitive Model of the Internal Combustion Engine. SAE Technical Paper Series. https://doi.org/10.4271/2018-01-1738
51. Kuric, I., Gorobchenko, O., Litikova, O., Gritsuk, I., Mateichyk, V., Bulgakov, M., Klackova, I. (2020). Research of vehicle control informative functioning capacity. IOP Conference Series: Materials Science and Engineering, 776 (1), 012036. https://doi.org/10.1088/1757-899x/776/1/012036
52. Mateichyk, V. P., Navrotskyi, A. V. (2024). Systematization of hardware schemes of vehicle operation monitoring systems. Reporter of the Priazovskyi State Technical University. Section: Technical sciences, 48, 184–192. https://doi.org/10.31498/2225-6733.48.2024.310711
53. Karshyga, A., Tulegulov, A., Kalkenov, A., Aryngazin, K., Nurtai, Z., Yergaliyev, D. et al. (2023). Development of an intelligent system automating managerial decision-making using big data. Eastern-European Journal of Enterprise Technologies, 6 (3 (126)), 27–35. https://doi.org/10.15587/1729-4061.2023.289395
54. Lebid, I., Luzhanska, N., Lebid, I., Mazurenko, A., Roi, M., Medvediev, I. et al. (2023). Development of a simulation model of the activities of a transport and forwarding enterprise in the organization of international road cargo transportation. Eastern-European Journal of Enterprise Technologies, 6 (3 (126)), 6–17. https://doi.org/10.15587/1729-4061.2023.291039
55. Bugayko, D., Ponomarenko, O., Sokolova, N., Leshchinsky, O. (2023). Determining possibilities for applying theoretical principles of situational risk management in the aviation safety system. Eastern-European Journal of Enterprise Technologies, 6 (3 (126)), 55–66. https://doi.org/10.15587/1729-4061.2023.294763
56. Golovan, A., Gritsuk, I., Popeliuk, V., Sherstyuk, O., Honcharuk, I., Symonenko, R. et al. (2019). Features of Mathematical Modeling in the Problems of Determining the Power of a Turbocharged Engine According to the Characteristics of the Turbocharger. SAE International Journal of Engines, 13 (1). https://doi.org/10.4271/03-13-01-0001
57. New European Driving Cycle (NEDC). Available at: https://www.transportpolicy.net/standard/eu-light-duty-new-european-driving-cycle/

58. Emissions of air pollutants from transport in Europe. Available at: https://www.eea.europa.eu/en/analysis/indicators/emissions-of-air-pollutants-from
59. Volodarets, M., Gritsuk, I., Ukrainskyi, Y., Shein, V., Stepanov, O., Khudiakov, I. et al. (2020). Development of the analytical system for vehicle operating conditions management in the V2I information complex using simulation modeling. Eastern-European Journal of Enterprise Technologies, 5 (3 (107)), 6–16. https://doi.org/10.15587/1729-4061.2020.215006
60. Roberts, A., Brooks, R., Shipway, P. (2014). Internal combustion engine cold-start efficiency: A review of the problem, causes and potential solutions. Energy Conversion and Management, 82, 327–350. https://doi.org/10.1016/j.enconman.2014.03.002
61. Kovalchuk, V. V., Moisieiev, L. M. (2008). Osnovy naukovykh doslidzhen. Kyiv: Vydavnychyi dim "Profesional", 230.
62. Hryshchuk, Yu. S. (2008). Osnovy naukovykh doslidzhen. Kharkiv: NTU "KhPI", 232.