

The Evaluation of Vehicle Fuel Consumption and Harmful Emission Using the Heating System in a Driving Cycle

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ABSTRACT

The article suggests the results of experimental and theoretical studies of the engine heating system with a phase-transitional thermal accumulator when the vehicle is in motion in a driving cycle. The aim of the study is to evaluate the efficiency of the vehicle heating system within thermal accumulator and catalytic converter under operating conditions. The peculiarity of the presented system is that it uses thermal energy of exhaust gases to accumulate energy during engine operation. The article describes the methodology to evaluate vehicle fuel consumption and emission in the driving cycle according to the UNECE Regulation № 83-05. The methodology takes into account the environmental parameters, road conditions, the design parameters of the vehicle, the modes of its motion, thermal state of the engine cooling system and the catalytic converter. Experimental studies determined the patterns of changing technical parameters of the engine G4GC (4FS 7.72 / 8.45) in the heating process using the heating system with thermal accumulator. Mathematical modelling techniques enabled to obtain quantitative values of fuel consumption and emission of KIA CEE'D 2.0 5MT2 in the driving cycle.

The analysis of the research results showed that using the vehicle heating system can significantly reduce the time of heating the engine, fuel consumption and harmful emission under operating conditions.

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INTRODUCTION

To provide optimal temperature condition of the internal combustion engine (ICE) and the vehicle during pre-start and after-start thermal development and the operation of the vehicle is a complicated task. It can be solved using systems research methods. It is necessary to influence the main systems objects of the ICE and the vehicle. They are: a coolant, motor oil, catalytic converter (CC) of the exhaust gases cleaning system of the ICE and the vehicle interior at low ambient temperatures. For simultaneous impact on the systems objects, the combined heating of the ICE and the vehicle can be used. It can be done due to the combined heating system (CHS) based on phase- transitional thermal accumulators (TA) with heat accumulating material (HAM) [1].

To determine the parameters of optimal temperature of the engine and the vehicle under operating conditions, it is advisable to develop methodological bases. They help evaluate fuel economy and environmental performance of the vehicle equipped with the heating system when the vehicle is in motion. The methodology takes into account the environmental parameters, road conditions, design parameters of the vehicle, modes of its motion, thermal state of the catalytic converter and the engine cooling system.

To solve this problem, the research was conducted at the departments of Kharkiv National Automobile and Highway University (KhNAHU) and National Transport University (NTU). The researchers developed and investigated the CHS components of the vehicular engine with phase-transitional TA [1]. They also developed and improved basic elements of mathematical models for evaluating fuel economy and environmental performance of internal combustion engines and vehicles under operating conditions [2]. Computer integrated technology to control transport operation was developed and adapted for use. It ensured the creation of monitoring systems to obtain information about separate vehicles, to study their diagnostic parameters and to forecast the technical condition of the vehicle [3] during operation in terms of ITS (Intelligent transport system) information capabilities [4].

THE PECULIARITIES OF THE ENGINE AND THE VEHICLE HEATING SYSTEM

The peculiarities of the heating system are detailed in [5]. The peculiarities of the monitoring system to learn the condition parameters are detailed in [6].

The research was conducted under corresponding laboratory conditions with the designed test stands. The researchers studied the heating system elements in order to choose HAM, the development of phase-transitional TA design, the improvement of the technology of the vehicular engine thermal development and the optimization of pre-start and after-start development with engines and without them.

Experimental studies were conducted using the monitoring system of technical condition parameters of the vehicle [5, 6]. The main objects of experimental studies were: under laboratory conditions - inline engine 6FS 12/14 [1] and under operating conditions - inline engine G4GC of a passenger car KIA CEE'D 2,0 5MT2 [6] and a V-shaped truck engine 8FS 9.2/8 [5]. The vehicles were equipped with the heating system. The results of experimental studies are thoroughly analyzed in [5, 6].

The results of experimental studies show that using the heating system can reduce the total engine heating period by 17.8 - 68.4% and fuel consumption for heating by 19.5 - 56.25%. It depends on the ambient temperature and heating mode of the engine (idling, heating in motion, etc.). However, in order to determine the impact of using the heating system on total fuel consumption and harmful emission of the vehicle, it is necessary to conduct a research when the vehicle is in motion under certain predefined conditions.

GENERAL RESEARCH METHODOLOGY TO STUDY VEHICLE PERFORMANCE IN MOTION USING THE HEATING SYSTEM

In order to determine the effect of the developed heating system on fuel economy and environmental performance of the vehicle considering its heating during the motion, a corresponding research methodology was developed. The methodology is based on the use of a mathematical model of the "engine-catalytic converter" system [2].

The object of further studies to calculate fuel economy and environmental performance of the vehicle equipped with the heating system is KIA CEE'D 2.0 5MT2 with the installed engine G4GC. [Table 1](#) shows vehicle technical parameters necessary for calculations.

The research methodology involves evaluating fuel economy and environmental performance in typical modes of the vehicle motion. It ensures adequate comparison of these parameters for different conditions of heating the vehicular engine. For further research, therefore, the driving cycle according to the UNECE Regulation № 83-05 [7] was chosen as a set of typical modes of the vehicle motion. This cycle is used to evaluate the parameters of the vehicle environmental safety, i.e. harmful emission and fuel economy of passenger cars and light-duty trucks. The cycle includes four elementary urban cycles with a total length 4.052 km, a duration 780 s and a maximum speed 50 km/h and extra-urban cycle with a length 6.955 km, a duration 400 s and a maximum speed 120 km/h.

To study the nature of the ambient temperature influence on the efficiency of the developed heating system, it was decided to perform the calculations provided the ambient temperature was -20 °C, 0 °C and 20 °C. Such temperature conditions differ from the recommended ones to test the driving cycle (20 - 30 °C). So, the research results

cannot be used to establish the compliance with environmental standards. The results are used only to evaluate the efficiency of the developed heating system.

Table 1. Technical parameters of KIA CEE'D 2.0 5MT2 with the engine G4GC

Title	Specification
Weight of the vehicle with a driver, kg	1500
Maximum speed, km/h	205
Fuel type	petrol
Number / arrangement of engine cylinders	4 / inline
Engine displacement, l	1.975
Diameter of cylinder / piston stroke, mm	82 / 93.5
Compression ratio	10.1
Engine power, kW / crankshaft rotation speed, min ⁻¹	105 / 6000
Torque, N·m / crankshaft rotation speed, min ⁻¹	186 / 4600
Number of inlet / exhaust valves per cylinder	2 / 2
Exhaust gases cleaning system	three-component catalytic converter
Gearbox ratios	3.308
	1.962
	1.257
	0.976
	0.778
Final drive ratio	4.188
Wheel rolling radius, m	0.285

The basis of the mathematical model for modes of the driving cycle to simulate the vehicle motion is determining the required engine M_e torque and crankshaft rotation speed n_e . They provide appropriate values of speed V_v and acceleration j_v of the car.

In sections of acceleration, the values of the required torque and crankshaft rotation speed are determined at the starting and end points of these sections for similar conditions in steady modes. It is considered that the change of the engine performance is linear. The engine control system disables fuel supply while driving in a mode of compulsory idling. So, when slowing with the clutch pedal pressed down, the required torque is not determined. It is assumed that there are no fuel consumption and emission of harmful substances. When slowing with the clutch pedal up, then it is assumed that crankshaft rotation speed corresponds to the minimum idling rotation speed.

THE GENERAL STRUCTURE OF THE SIMULATION ALGORITHM OF THE VEHICLE PERFORMANCE

[Fig. 1](#) shows the developed algorithm of the mathematical model to study fuel economy and environmental performance of the vehicle considering heating in motion.

At the beginning of the calculations the initial data are input in blocks 1-3.

Blocks 1 and 2 determine vehicle parameters. These include the parameters specified in Table 1.

Block 3 determines the parameters of the road and the environment: rolling resistance coefficient ψ , atmospheric pressure p_0 , Pa, the ambient temperature T_0 , K.

Blocks 4 - 8 of the algorithm prepare the necessary initial data for the mathematical model "engine-catalytic converter". Thus, block 4 determines operating mode parameters of the vehicular engine at the current time: τ_i is the current value of time from starting the engine, s, n_{ei} is the current value of crankshaft rotation speed, min^{-1} , M_{ei} is the current value of the effective torque of the engine, N·m.

Block 5 determines the ignition timing angle θ_p , degrees of crankshaft rotation, as a function $\theta_i = f(n_{ei}, M_{ei})$. Block 6 determines the temperature in the inlet manifold of the engine $t_{inlet i} = f(p_0, T_0, n_{ei}, M_{ei})$, °C. Block 7 determines the initial values of the coolant temperature $t_{cool i} = T_0 - 273$, °C.

Block 8 determines the current values of crankshaft rotation speed n_{ei}^{idling} in an idling mode and excess air coefficient λ_i as a function of $t_{cool i}$: $n_{ei}^{idling} = f(t_{cool i})$, $\lambda_i = f(t_{cool i})$.

All prepared initial data enter block 9, where the calculations are performed on the mathematical model of the "engine-catalytic converter" system. On leaving the model of the system all further calculations are performed in 3 parallel directions. They consistently identify groups of main energy, fuel economy and environmental performance of the engine and the vehicle.

Block 10 (Fig. 1) determines average frictional pressure loss in the engine $p_{FR i} = f(t_{cool i})$, Pa. Block 11 determines average pumping pressure loss $p_{PUMP i}$, Pa, and average indicating pressure of the operating cycle $p_{OC i}$, Pa, of the vehicular engine. Block 12 determines the moment of mechanical loss $M_{Mi} = f(p_{FR i}, p_{PUMP i})$, N·m, and indicating torque $M_{OC i} = f(p_{OC i})$, N·m, of the vehicular engine. Block 13 determines the estimated effective torque: $M_{ei}^{EST} = M_{OC i} - M_{Mi}$, N·m.

Block 14 checks whether the values of the estimated M_{ei}^{EST} correspond with the required effective torque M_{ei} of the vehicular engine. If $M_{ei}^{EST} \neq M_{ei}$, then a further calculation is performed in block 15. It determines the adjusted value of the throttle opening angle $\varphi_{thr i}$ considering the value of the throttle opening angle adjustment $\Delta\varphi_{thr i}$ (degrees), namely $\varphi_{thr i} = \varphi_{thr i} \pm \Delta\varphi_{thr i}$. If the condition $M_{ei}^{EST} \neq M_{ei}$ is not met, then a further calculation is performed in block 24.

Block 16 determines the amount of heat removed from the working fluid in the cylinder into the cooling system per one operating cycle Q_{Ti}^C . It takes into account the amount of heat that is removed from the working fluid in the cylinder into the cooling system per the j-th estimated period of operating cycle dQ_{Tj} : $Q_{Ti}^C = \sum_{j=1}^n dQ_{Tj}$, J,

and EG temperature in the exhaust manifold $t_{EG i} = f(n_{ei}, M_{ei}, T_0)$, °C. When using the CHS [1] with phase-transitional TA, block 16 additionally adjusts the amount of heat removed from the working fluid in the cylinder into the cooling system to the value of additional coolant heating from the CHS elements during pre-start and after-start thermal development of the ICE and the vehicle. This takes into account the heat accumulated in phase-transitional TA of the CHS elements [1]:

$$Q_{TA} = m_H \cdot \int_{T_1}^{T_{PH}} C_{SOL}(T) dT + m_H \cdot r_T + m_H \cdot \int_{T_{PH}}^{T_2} C_{LIQ}(T) dT, \quad (1)$$

where m_H is the weight of HAM that undergoes a phase transition of melting-solidification, kg; $C_{SOL}(T)$, $C_{LIQ}(T)$ is specific mass heat capacity of HAM depending on the temperature, in solid and liquid phases respectively, J/(kg·K); r_T is specific thermal energy of melting-solidification phase transition, J/kg; T_1 , T_2 , T_{PH} are temperatures of HAM: initial, final and phase transition respectively, K.

Block 17 determines fuel consumption per hour $G_{FUEL i}$, kg/h, and air consumption per hour $G_{AIR i}$, kg/h, of the vehicular engine. Then, block 18 determines exhaust gas flow per hour, $G_{EG i}$, kg/h. Block 19 determines the coolant temperature $t_{cool i+1} = f(t_{cool i}, Q_{Ti}^C)$, °C, and the temperature of the catalytic converter unit $t_{CAT i} = f(G_{EG i}, n_{ei}, t_{EG i})$, °C.

The environmental performance of the engine and the vehicle is determined in blocks 20 - 23. Block 20 determines the concentration of CO (%), $C_m H_n$ (ppm), NO_x (ppm) before the catalytic converter: $(CO_i, C_m H_n i, NO_{xi}) = f(n_{ei}, M_{ei}, \lambda_i)$. Block 21 determines the efficiency of cleaning CO, $C_m H_n$, NO_x , %, namely: $(E_{CO i}, E_{CH i}, E_{NOx i}) = f(\lambda_i, t_{CAT i})$. Block 22 determines the concentration of CO (%), $C_m H_n$ (ppm), NO_x (ppm) after the catalytic converter, namely: $(CO_i^{CAT}, C_m H_n i^{CAT}, NO_{xi}^{CAT}) = (CO_i, C_m H_n i, NO_{xi}) \cdot (1 - (E_{CO i}, E_{CH i}, E_{NOx i}) / 100)$. In addition, block 23 determines the mass emission of CO, $C_m H_n$, NO_x , (kg/h), namely:

$$(G_{CO i}, G_{C_m H_n i}, G_{NO_x i}) = f(\lambda_i, G_{FUEL i}, G_{AIR i}, (CO_i^{CAT}, C_m H_n i^{CAT}, NO_{xi}^{CAT})).$$

After determining the main energy, fuel economy and environmental performance of the engine and the vehicle, block 24 changes the serial number of the calculation cycle to the next one, $i = i + 1$. Block 25 changes the current time from starting the vehicular engine: $\tau_i = \tau_{i-1} + 120/n_{ei-1}$, s.

The general methodology and the research algorithm enable to evaluate the effectiveness of operating the vehicle equipped with the heating system and catalytic converter. It is based on the analysis of the current and total values of fuel consumption and harmful emission of the vehicle in motion in the driving cycle.

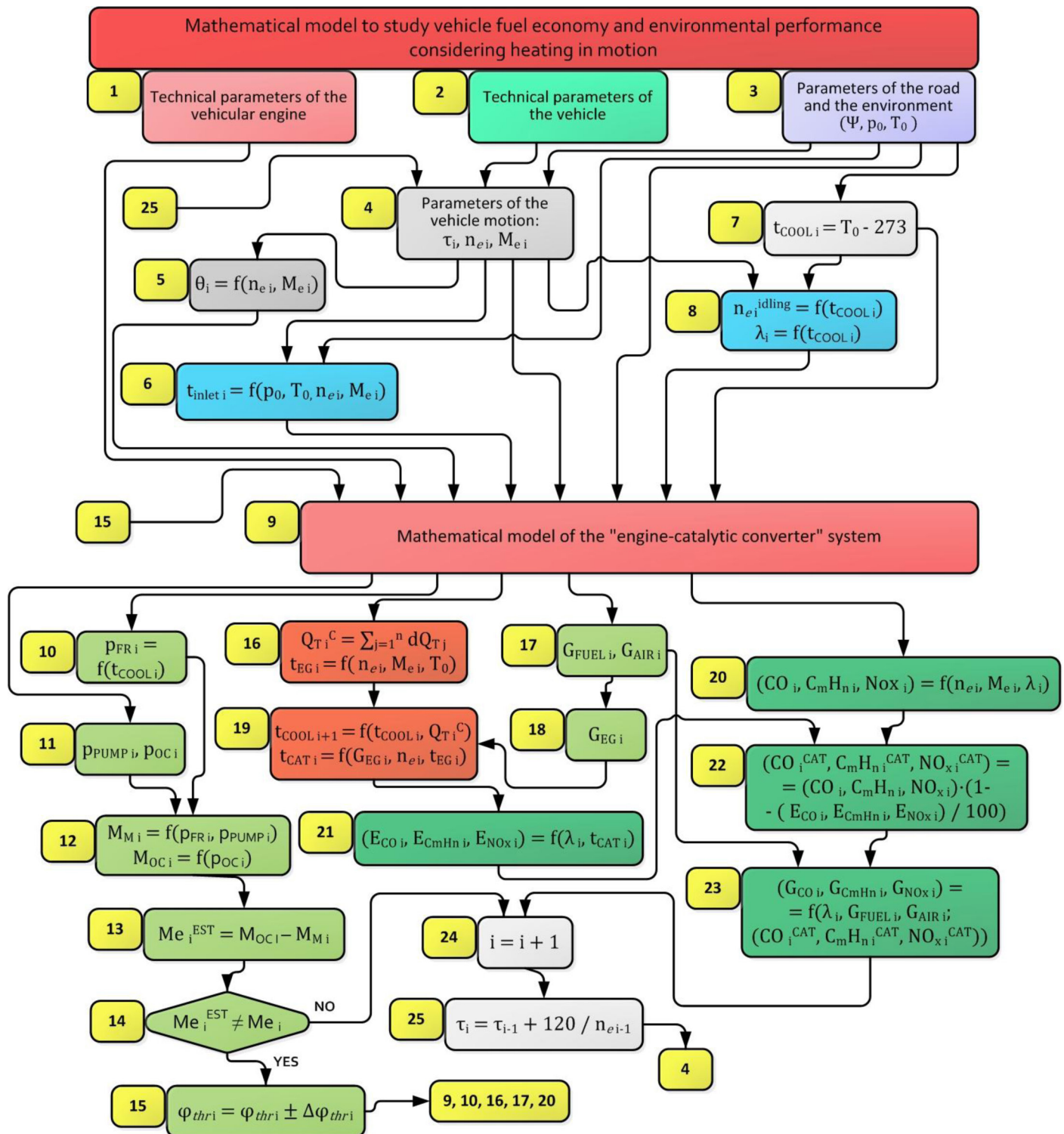


Figure 1. The research algorithm to study fuel economy and environmental performance of the vehicle considering heating in motion

THE PECULIARITIES OF SIMULATING THE "ENGINE-CATALYTIC CONVERTER" SYSTEM

To simulate the basic performance of the vehicular engine under certain operating conditions, a systems approach is applied. It allowed the researchers to present the operating process of the engine as a functional structure of the "engine-catalytic converter" system. It is shown in Fig. 2.

There are two main processes in the system: the conversion of fuel chemical E_{CH} energy into thermal energy E_T and then in mechanical energy E_M (level A) and cleaning harmful EG components in the catalytic converter (level C). System processes are controlled due to feedback (levels B and D).