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D. Trifonov (https://orcid.org/0000-0001-9723-269X)
O. Dobrovolskiy (https://orcid.org/0000-0003-0048-1388)
M. Romanenko (https://orcid.org/0009-0006-8366-6714**)**
P. Marchenko (https://orcid.org/0009-0000-3870-2815)

National transport university, 1 Mykhaila Omelianovycha-Pavlenka str.,
Kyiv, 01010, Ukraine

Corresponding author: D. Trifonov, e-mail: *d.trifonov@ntu.edu.ua*

Thermoelectric System for Intake Air Temperature Optimization in Toyota Prius: Modeling and Efficiency Assessment

This study presents a comprehensive investigation into the application of thermoelectric modules for adaptive, bidirectional control of intake air temperature in the gasoline internal combustion engine (ICE) of a hybrid Toyota Prius (XW30) operating on gasoline–ethanol fuel blends. The research analyses the impact of low ambient temperatures on fuel economy and environmental performance when using bioethanol-based fuels, the physicochemical properties of bioethanol, and the operational characteristics of the hybrid powertrain. Based on the calculated number of thermoelectric modules required, a system design is proposed that integrates with the vehicle's regenerative braking system to improve energy efficiency. Mathematical modelling results of the proposed thermoelectric system are presented, demonstrating its potential to enhance ICE adaptability to alternative fuels under varying environmental conditions. The findings indicate that such an adaptive thermoelectric system can contribute to improved fuel efficiency, reduced emissions, and compliance with increasingly stringent environmental regulations.

Keywords: hybrid powertrain; internal combustion engine (ICE); cold start and engine warm-up; intake air temperature; thermoelectric module (TEM); adaptive thermal management; gasoline–ethanol fuel; bioethanol; regenerative braking; fuel economy; environmental performance; alternative fuels; vehicle energy efficiency.

Introduction

The world faces a ternary challenge, i.e., growing energy demand, intensification of environmental problems (including climate change and air pollution), and instability in fuel markets [1]. The transport sector is strongly dependent on internal combustion engines (ICE),

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those being a key consumer of fossil fuels, as well as a source of pollutant and greenhouse gas emissions [2].

In this context, finding ways to improve the efficiency of existing technologies, especially gasoline internal combustion engines, which remain dominant in passenger vehicles, is becoming critical.

One promising strategy is the use of alternative fuels, in particular benzoethanol blends [3, 4]. Bioethanol, derived from biomass, offers the potential to reduce CO_2 emissions and increase the octane rating of fuels. However, its use is accompanied by certain technical difficulties, mainly related to its volatility and high heat of vaporization.

In this very context the technology of heating the air at the intake looks promising, and its proper application, especially with benzoethanol blends, can become a powerful catalyst for improving the energy, environmental and fuel-economic performance of ICEs, primarily when modernizing used cars in operating conditions.

The use of thermoelectric modules for precise, fast and bidirectional control of the air temperature at the intake of the ICE will allow significant optimization of the processes of mixture formation, combustion and filling of engine cylinders when using benzoethanol fuel. This, in its turn, will lead to a comprehensive improvement of energy efficiency, fuel economy and a reduction in pollutant emissions, in particular CO_2 in exhaust gases. [5, 6]

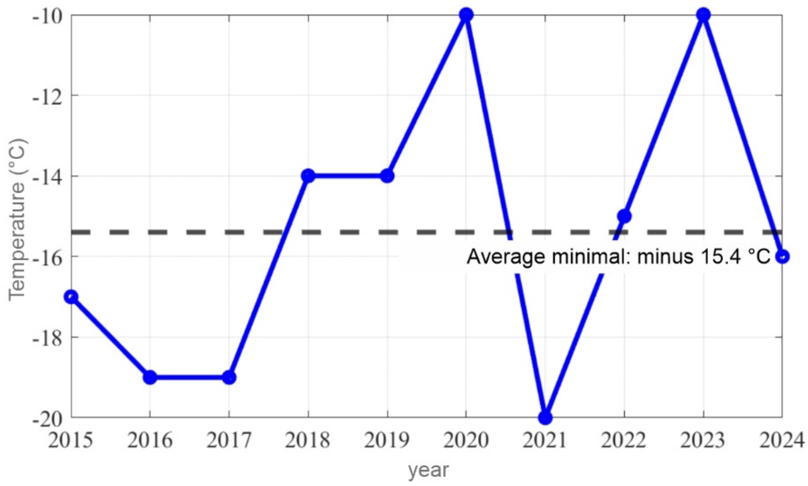
Therefore, research concerning studying the influence of operating conditions of motor vehicles using alternative fuels on their operational performance are an important scientific task that determines the possibility of widespread introduction of alternative fuels in the future.

Analysis of previous research

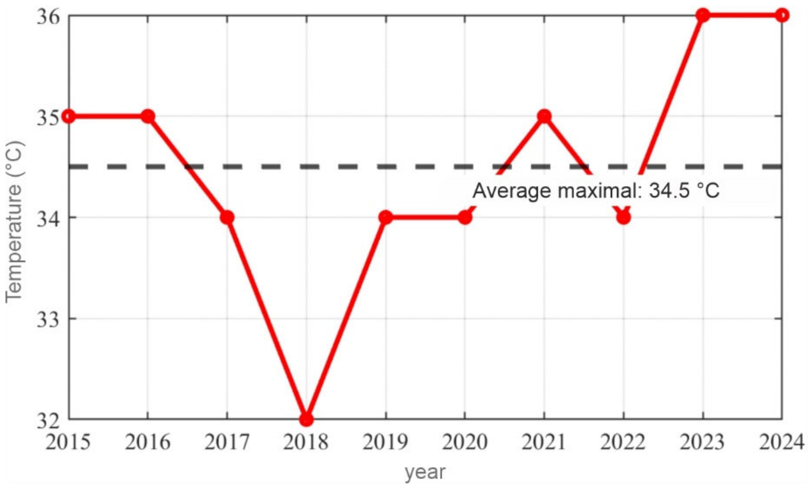
As it has already been noticed, the use of alternative fuels, in particular the replacement of part of commercial gasoline with bioethanol, which, based on the peculiarities of physicochemical properties that differ from those of gasoline, requires additional technical solutions to ensure improved operational characteristics of ICEs in various operating conditions, such as low or extremely high ambient temperatures (Fig. 1).

Based on the analysis of the data obtained for further calculation studies, we assume the minimum air temperature at the intake to be minus 15 °C, and the maximum temperature to be +60 °C. (A possible increase in temperature in the underbonnet space by 15…25 °C due to intensive heat generation of the ICE is taken into account.) Since the optimal temperature of the intake air is 30…40 °C, it is necessary to maintain it in this range in different operating modes of the ICE. (Fig. 2)

With using E40…E85 benzoethanol fuels in a Toyota Prius (XW30) car, two main challenges are revealed. The first is the complicated start of a cold ICE and the extended warm-up time due to the high heat of vaporization of ethanol (844 kJ/kg versus 350 kJ/kg in gasoline). The second is detonation phenomena at maximum load due to the increased intake air temperature. The use of E0…E20 blends has practically no effect on the ICE operating process [8].



a



b

Fig. 1. Average minimum (a) and maximum temperatures (b) in Kyiv for the period from 2015 to 2024 [7]

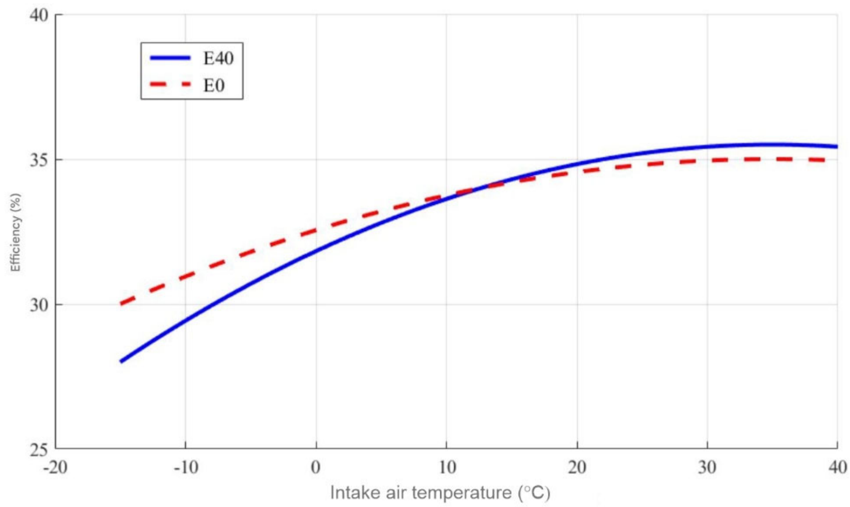


Fig. 2. Overall engine efficiency depending on the intake temperature: E40 (60 % gasoline + 40 % bioethanol), E0 (100 % gasoline + 0 % bioethanol) (numerical modeling and visualization of results were performed in the MATLAB environment)

Based on the analysis of the thermodynamic properties of benzoethanol blends, the following optimal average air temperatures at the engine intake were established [9]:

1. In cold engine start modes, increasing the temperature to +15 °C and warming up to +40 °C (compensation of the heat of ethanol vaporization and reduction of mechanical losses).

2. In maximum power mode, reducing the air temperature to +40 °C (increasing the filling coefficient and preventing the possibility of detonation).

The choice of a specific method for maintaining these temperatures depends on the design features of the vehicle's power plant, operating conditions, and the economic feasibility of using a particular method [9-15].

Traditional methods of temperature control of air at the intake of an ICE are:

- standard (Exhaust Gas Recirculation, EGR) system;
- electric heating element (Positive Temperature Coefficient, PTC);
- thermal accumulator based on phase change materials (Phase Change Material, PCM accumulator);
- adaptive air filter heater;
- thermoelectric module.

Each of these methods has its advantages and limitations in terms of reaction speed, energy efficiency and complexity of implementation.

According to the authors, the most effective technical solution for the use of benzoethanol blends is, actually, thermoelectric thermoregulation of air at the intake. It allows:

• ensuring reliable start-up of a cold internal combustion engine and accelerating the process of restoring its thermal mode;

• reducing the time for the catalytic converter (CCT) to enter the mode of effective operation;

• cooling the air to +40 °C under load, increasing the filling ratio, detonating reserve and reducing NO_x emissions.

Based on the analysis of the design features of the *Toyota Prius* (XW30) hybrid car, the conditions of its operation in Kyiv, together with the cost of modifying the fuel supply system and upgrading the engine in order to maximize the efficiency of using benzoethanol fuel, to maximize the efficiency of using benzene-ethanol fuel, the installation of thermoelectric modules as additional equipment for maintaining optimal air intake temperature is proposed.

To the most significant advantages of thermoelectric modules the following are related [9]:

• compact mass and dimensions, enabling their integration into the limited spaces of the engine compartment;

• absence of moving parts, minimal maintenance requirements;

• high heating and cooling rate with sufficiently low energy consumption, which ensures a prompt response to changes in the operating modes of the ICE;

• high energy efficiency, which contributes to the overall increase in fuel economy of the vehicle and the extension of the service life of the battery (AB)

The above considered, thermoelectric modules combine ease of integration with high flexibility in regulating the air temperature at the intake, thus making them the optimal solution for adapting the *Toyota Prius* to operate on benzoethanol blends.

The hybrid power plant of the *Toyota Prius* has unique facilities for integrating thermoelectric systems:

• high-voltage bus (traction battery voltage is 201.6 V);

• the possibility of recuperation of braking energy, i.e., the energy spent, for example, on accelerating the car from 0 to 60 km/h, can be partially recovered during braking. The amount of recovered energy can be about 0.02…0.035 kW·h of electrical energy, which is subsequently accumulated in the electrochemical capacitor module;

• reducing the load on the high-voltage battery in the cold start mode of the internal combustion engine by using the electrochemical capacitor module;

• intelligent control via the CAN interface.

The application of thermoelectric modules often allows for a simple solution to complex technical problems of thermal energy management and provides significant advantages over alternative technologies (Table 1).

<u>*Table 1*</u>

Comparison with alternative technologies [9–11]

Parameter	Thermoelectric modules	Electric PTC heater	Intercooler
Response speed, s	<1	1...3	>10
Energy efficiency, %	60…70	30…40	–
Weight and overall dimensions	compact sized	more difficult to integrate	requires significant space
Maintenance	minimal	minimal	periodic fluid replacement, cleaning
Intelligent control	ia CAN bus, PID algorithms	simplified relay	without active control

Research results

Taking into account the requirements for minimizing interference with the design of the ICE and the systems that ensure its operation, as well as modern technological solutions, the authors, considering the previously developed thermoelectric system [9, 16], proposed a scheme with an electrochemical condenser module (Fig. 3). The developed system provides improved performance characteristics of a hybrid vehicle under conditions of extreme ambient air temperatures by automatically maintaining the optimal air temperature at the intake.

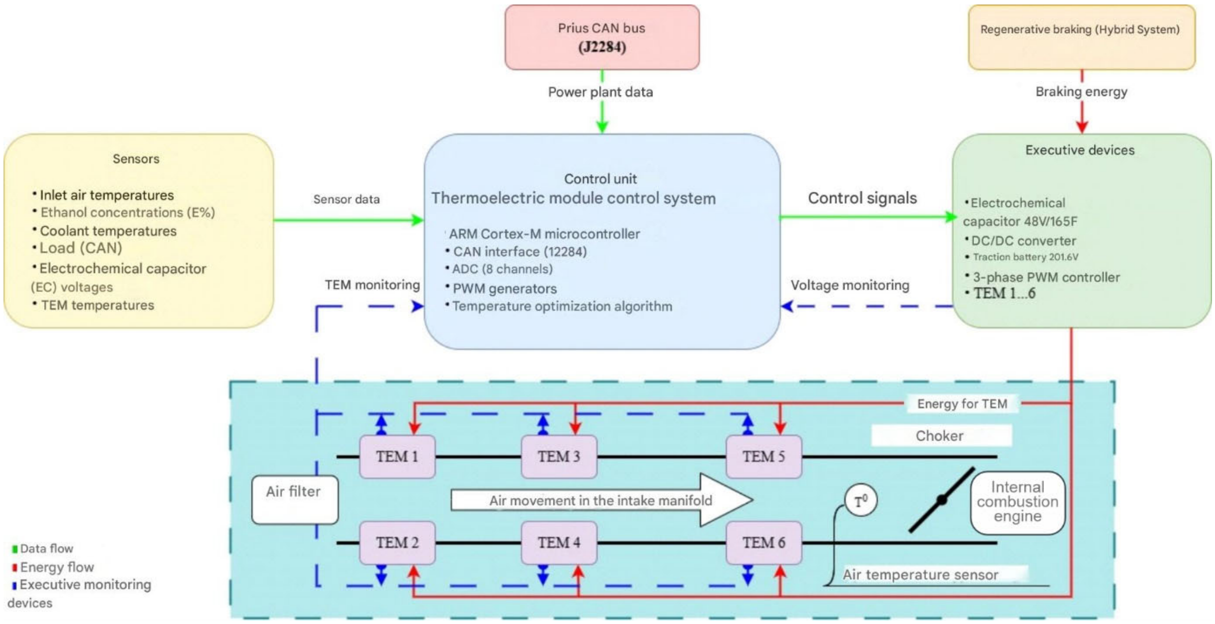


Fig. 3. Proposed schematic diagram of a thermoelectric system

The development takes into consideration the design features of the hybrid power plant and provides for the use of an electrochemical condenser module, which, accumulating electrical energy during braking, powers the thermoelectric modules in the following modes:

1. cold engine start;
2. engine warm-up;
3. operation at maximum loads.

For the calculation studies, the following initial data were determined (Table 2):

1. *Toyota Prius* (XW30) car, THS-II hybrid power plant (Toyota Hybrid System II), 2ZR-FXE gasoline engine, 1.8 l capacity [17, 18].

2. E40 gasoline ethanol fuel (60 % gasoline + 40 % bioethanol). The use of E85 requires a deeper modernization of the power plant due to the increased aggressiveness of ethanol towards rubber and aluminum and requires more frequent diagnostic checks of the ICE.

3. Internal combustion engine operating modes:
 - cold engine start: up to 5 s.
 - warm-up: up to 300 s. (until the coolant temperature reaches about 70 °C);
 - maximum power: up to 30 s.

4. Temperature changes, ΔT (°C), i.e., the difference between the final and initial temperatures in the specified operating modes of the ICE:
 - start-up: heating $\Delta T = 30°$ (from minus 15 °C to +15 °C);
 - warm-up: heating $\Delta T = 55°$ (from minus 15 °C to +40 °C);
 - maximum power: cooling $\Delta T = 20°$ (from +60 °C to +40° C).

Table 2

Input data for further calculations

ICE operating mode	Crankshaft speed, min^{-1}	Duration, s	Temperature change,°C
Cold start	250	5	increase by 30
Warm-up	900	300	increase by 55
Maximum power	5200	30	decrease by 20

Further data processing, statistical analysis, numerical modeling and visualization of results (graphs, diagrams) were carried out in the MATLAB environment using its built-in software and computational capabilities.

The following factors were not taken into account when conducting computational studies in the MATLAB environment:

1. heat losses in pipelines;
2. dynamics of changes in relative air humidity;
3. influence of altitude;
4. operational characteristics of the air filter;
5. pressure losses at the intake.

The following data were obtained from the calculations (Table 3).

Table 3

Estimated number of TEMs required to stabilize the intake air temperature under variable operating conditions of the ICE

ICE operating mode	Air volume flow rate, Q_v, m^3/s	Mass air flow rate, Q_m, kg/s	Total air flow rate, kg	Thermal power $P_{heat/cool}$, W	Thermal energy E_{heat}, kJ	Electric power of TEM taking into account COP, W	Number of TEMs
Cold start	0.0032	0.0043	0.0066	129.7	*heating* 0.7	185.3	1
Warm-up	0.0097	0.013	1.37	*heating* 725.0	*heating* 217.5	1035.7	4
Maximum power	0.067	0.07	2.16	*cooling* 1413.0	*cooling* 42.4	2826.1	6

Based on the analysis of the characteristics of the hybrid power plant, the physicochemical properties of bioethanol and modern thermoelectric modules [17–20], the criteria for selecting a TEM for the system for maintaining the optimal air temperature in the intake manifold of the *Toyota Prius* hybrid car were determined (Table 4). Possible TEM options for use in the selected car were also outlined (Table 5).

Table 4

Criteria for selecting a thermoelectric module for an intake air temperature stabilization system and recommended values of its parameters

Parameter	Unit	Value
1	2	3
Weight and overall dimensions	mm	compact, suitable for integration into the intake manifold
Operating voltage, U	V	36…48
Maximum current, I	A	15
Heating capacity, Q_h	W	600…800 (at $\Delta T = 0$°C)
Cooling capacity, Q_c	W	300..500 (at $\Delta T = 0$°C)
Maximum ΔT between sides	°C	≥ 60
Temperature range	°C	minus 30...+85
Power consumption	W	180
Coefficient of performance (COP) - heating: - cooling:	–	> 0.7 > 0.5
1	2	3
Mechanical stability and reliability - vibration resistance: - sealing:	–	≥ 5g (ISO 16750-3). protection against moisture and dust (IP67)
Materials: -case: - elements: - insulation:	–	anodized aluminum Bi_2Te_3 ceramic lining
Control Compatibility - PID Controllers: - Sensors:	–	integration with the vehicle's CAN bus for adaptive PWM. support for type K thermocouples or digital sensors (DS18B20).
Service life	hours	high cyclic stability (over 50.000 cycles)

Table 5

Possible variants of thermoelectric modules [19, 20]

Module type*	T_h, °C	ΔT_{max}, °C	Q_{max}, Вт	U_{max}, V	I_{max}, A	T_{max}, °C
Altec-CM-1-P-IEIU	27	70…74	45…205	30.8…225	0.005…5.7	150…200
TEC1-28826	30	68	524.16	34.92	26	150…200

* Special ones with increased efficiency and increased operating voltage

Mathematical modeling in the MATLAB environment was carried out to determine the influence of the air temperature at the intake on the main parameters of the *Toyota Prius* 2ZR-FXE engine operating on E40 fuel in warm-up mode. The calculations showed the following values of key indicators.

1. Influence on the quality of the fuel-air mixture. (Table 6)

Table 6

Effect of increasing intake air temperature on the quality of the fuel-air mixture in warm-up mode

Parameter	Intake air temperature	
	– 15 °C	+ 40 °C
Evaporation rate E40	60…70%	95…98%
Flame front velocity, *v*	25 m/s	35 m/s
Excess air ratio, λ	0.85…0.95	0.98 0.02

2. Effect on pumping losses due to changes in the throttle valve opening angle (Table 7, Fig. 4).

Table 7

Pumping losses of the 2ZR-FXE engine when using fuel grades E0 and E40 within the range of intake temperatures minus 15 °C ...+40 °C

Intake temperature, °C	Throttle valve opening angle, %		Pumping losses, kW	
	E40	E0	E40	E0
–15	13.0	10.2	3.441	3.464
0	15.0	12.0	3.421	3.450
15	18.3	14.7	3.382	3.424
25	20.3	17.0	3.356	3.399
40	21.4	21.2	3.340	3.343

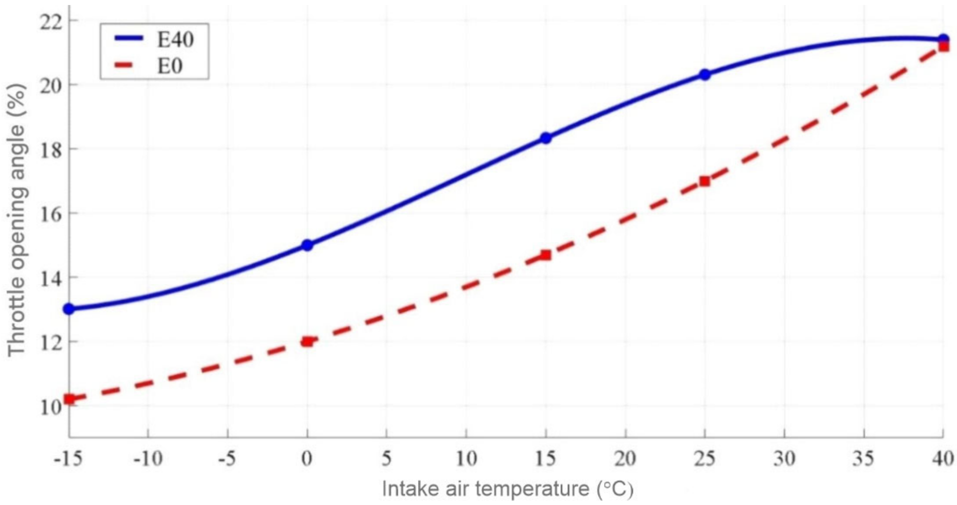


Fig. 4. Throttle valve opening angle depending on intake temperature

Heating the intake air to +40 °C when using E40 fuel can reduce pumping losses by 0.101 kW (2.94 %).

`1. Effect on the time and speed of engine warm-up and the dynamics of coolant temperature changes. (Fig. 5)

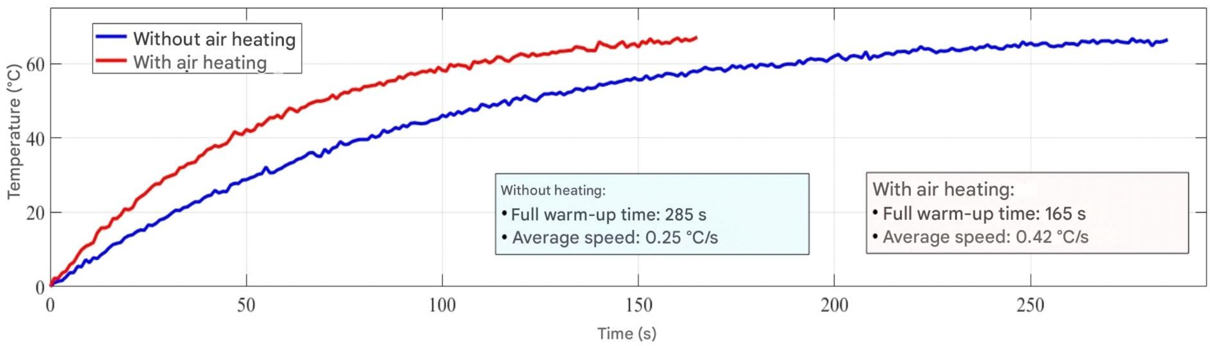


Fig. 5. Dynamics of coolant temperature change

Heating the intake air to +40 °C when using E40 fuel can increase the average engine warm-up rate by 0.17 °C/s (68 %) and reduce the total warm-up time from the initial temperature of 0 °C to the target temperature of +70 °C by 120 s (42 %).

1. Effect on the dynamics of fuel consumption during engine warm-up (Fig. 6)

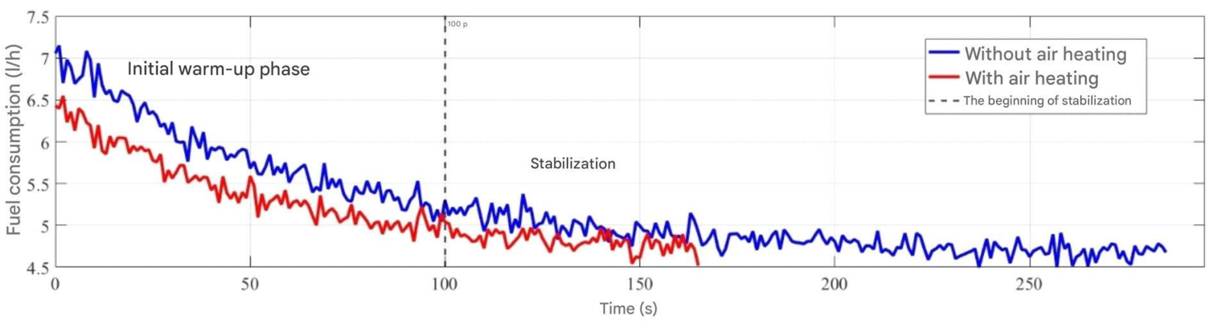


Fig. 6. Fuel consumption dynamics during engine warm-up of the 2ZR-FXE

Total fuel consumption for warming up:

- without air heating 317.40 g;
- with air heating 183.79 g.

Fuel savings due to heating:

- absolute savings 133.61 g;
- relative savings 42.1 %.

2. Impact on emissions of pollutants, including CO_2, with exhaust gases of internal combustion engines (Table 8, Fig. 7).

Table 8

Pollutant emissions and expected efficiency from increased intake air temperature in warm-up mode of the 2ZR-FXE engine when operating on E40 fuel

Substance	Intake temperature		Expected results of implementing the proposed method	
	minus 15 °C	+40 °C	Emission reduction	Efficiency, %
$C0_2$, g /(kW·hour)	950.0	780.0	170.0	17.9
CO, g /(kW·hour)	18.5	9.8	8.7	47.0
NO_x, g /(kW·hour)	8.2	5.5	2.7	32.9
C_mH_n, g/(kW·hour)	3.1	1.7	1.4	45.2

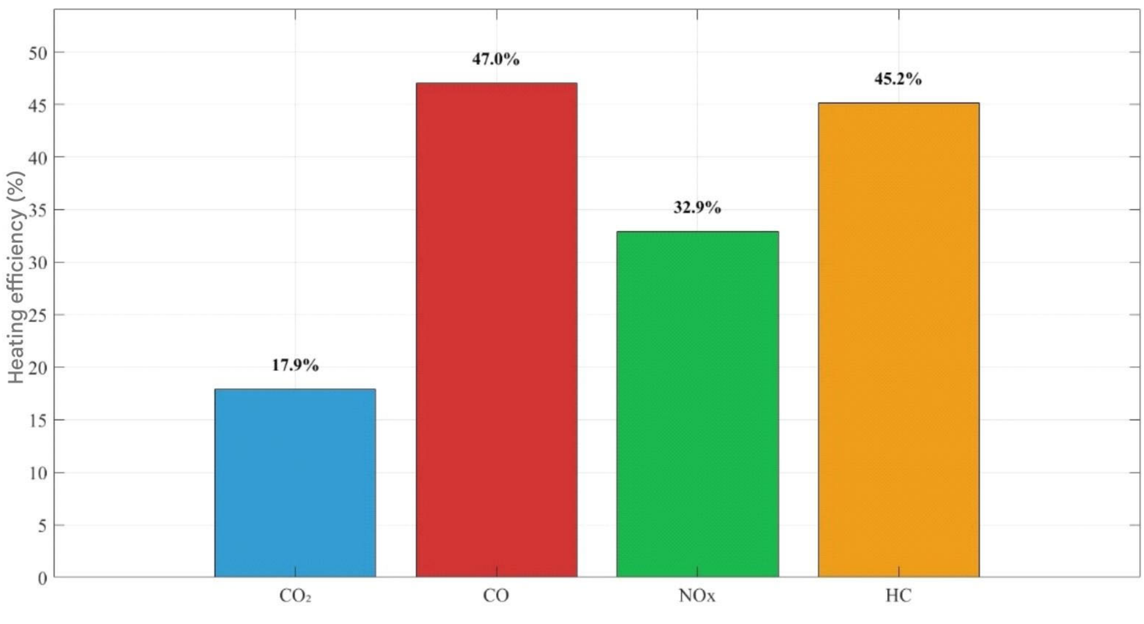


Fig. 7. Intake air heating efficiency

Further research is planned to focus on a combination of modeling, experimental verification and optimization of design and algorithmic solutions of the adaptive thermoelectric system.

It is planned to perform thermal modeling of the intake tract considering aerodynamic and thermal losses, the influence of humidity, condensation, icing and changes in air density to assess the efficiency of heat transfer. Maps of the coefficient of performance (COP) of thermoelectric modules depending on the temperature difference, thermal load and power modes should be formed in order to optimize control. At the algorithmic level, it is also necessary to implement predictive strategies based on CAN interface data and motion parameters for adaptive control of the intake air temperature depending on the load, ambient air temperature, state of charge of the electrochemical capacitor module and traction battery (AB).

The experimental part of the research will include bench and road tests in various climatic conditions, in particular in urban winter cycles with frequent cold starts, as well as an assessment of the reliability of the TEM (vibration resistance, thermal cycling, tightness, resistance to aggressive environments). Life Cycle Assessment (LCA) and cost-effectiveness analysis of the system implementation, including an assessment of CO_2 emissions using the Well-to-Wheel (WTW) approach and calculation of its payback period are scheduled as well.

Conclusions

1. In the paper the possibilities of increasing the efficiency of using benzoethanol fuel blends in hybrid vehicles using the example of Toyota Prius by integrating a thermoelectric system for heating the intake air are studied. This is important for reducing the dependence of road transport on fossil fuels thus reducing the negative impact on the environment.

2. It has been established that thermoelectric modules are a promising technology for the automotive industry, capable of increasing energy efficiency and environmental performance. The proposed system for heating the intake air ensures optimization of the engine thermal mode while operating on benzoethanol blends, which allows compensating for their disadvantages associated with evaporation and high heat of vaporization.

3. The implementation of adaptive thermal control of the intake air in hybrid vehicles contributes to increasing fuel efficiency, reducing pollutant emissions, and expanding the possibilities of using carbon-neutral bioethanol fuels in various operating conditions.

4. Mathematical modeling of the warm-up mode in the MATLAB environment for the *Toyota Prius* 2ZR-FXE engine when using E40 fuel showed the following results:

• reduction of the thermal mode recovery time by 42 %;
• increase in the average speed of internal combustion engine warm-up by 68%;
• increase in fuel efficiency by 42.1 %;
• overall reduction in emissions of harmful substances (CO, NOx, CmHn) by 41.7% and CO_2 by 17.9 %.

5. It is promising to conduct experimental tests of the proposed system in real operating conditions, alongside with studying its effectiveness for other types of alternative fuels and various models of both hybrid and traditional cars.

Authors' information

D. Trifonov – Associate Professor of the Department of Engines and Heat Engineering, Candidate of Technical Sciences, Associate Professor.
O. Dobrovolskiy – Professor of the Department of Engines and Thermal Engineering,

Candidate of Technical Sciences, Associate Professor.
M. Romanenko – postgraduate student of the Department of Engines and Thermal Engineering.
P. Marchenko – postgraduate student of the Department of Engines and Thermal Engineering.

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Тріфонов Д.М. (https://orcid.org/0000-0001-9723-269X),
Добровольський О.С. (https://orcid.org/0000-0003-0048-1388),
Романенко М.П. (https://orcid.org/0009-0006-8366-6714**),**
Марченко П.К. (https://orcid.org/0009-0000-3870-2815)

Національний транспортний університет,
вул. М. Омеляновича-Павленка, 1, Київ, 01010, Україна

Термоелектрична система оптимізації температури повітря на впуску автомобіля TOYOTA PRIUS: моделювання та оцінка ефективності

У статті представлено комплексне дослідження застосування термоелектричних модулів для адаптивного двоспрямованого регулювання температури повітря на впуску бензинового двигуна внутрішнього згоряння (ДВЗ) гібридного автомобіля *Toyota Prius* (XW30), що працює на бензоетанольному паливі. Проаналізовано вплив низьких температур навколишнього повітря на паливно-економічні та екологічні показники автомобіля, фізико-хімічні властивості біоетанолу, а також особливості гібридної енергетичної установки. На основі розрахунків необхідної кількості термоелектричних модулів запропоновано схему термоелектричної системи, що підтримує оптимальну температуру повітря на впуску автомобіля *Toyota Prius* з інтеграцією із системою рекуперації енергії гальмування. Наведено результати математичного моделювання роботи системи. Показано, що запропонована адаптивна термоелектрична система є перспективною технологією для підвищення ефективності та адаптації сучасних ДВЗ до використання альтернативних палив в умовах посилення екологічних вимог.

Ключові слова: гібридна енергетична установка, двигун внутрішнього згоряння, пуск та прогрівання холодного двигуна, температура повітря у впускному колекторі, термоелектричний модуль, адаптивне терморегулювання, бензоетанольне паливо, паливно-економічні та екологічні показники.

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