

Raising of Operating a Motor Vehicle Effects on Environment in Winter

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Abstract. Severe low-temperature conditions, in which considerable part of Russian Motor Park is operated, affect vehicles negatively. Cold weather causes higher fuel consumption and CO₂ emissions always. It is because of temperature profile changing of automobile motors, other systems and materials. For enhancement of car operation efficiency in severe winter environment the dependency of engine warm-up and cooling time on ambient air temperature and wind speed described by multifactorial mathematical models is established. -On the basis of experimental research it was proved that the coolant temperature constitutes the engine representative temperature and may be used as representative temperature of engine at large. The model of generation of integrated index for vehicle adaptability to winter operating conditions by temperature profile of engines was developed. the method for evaluation of vehicle adaptability to winter operating conditions by temperature profile of engines allows to decrease higher fuel consumption in cold climate.

1. Introduction

Motor vehicles play an important role in shaping our natural environment. Motor vehicles collectively contribute to a number of important and pressing ecology problems. Vehicles are a major source of air pollution, climate change, and urban sprawl.

Cold weather causes higher fuel consumption and CO₂ emissions from the nature of the things [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. It is because of temperature profile changing of automobile motors, other systems and materials [1, 3, 6, 7, 8, 9, 10].

The major part of Russia territory resides in the boreal, rigorous and cruel cold climate zones, accordingly the severe winter environment affecting the negative influence on performance indicators of rolling stock are typical for exploitation of motor vehicle fleet of the Russian Federation. The winter conditions primarily characterized by low temperature of ambient air which impact is compounded by the simultaneous wind exposure [1, 6].

Under the influence of winter environment the temperature profile of automobile motors varies essentially that can be attributed to rise of unit surface conductance to environment. In this regard, the warm-up time after start rises sharply and the shutdown cooling period thereof declines [6].

It has been established that the engines of vehicles of various brands and models under identically severe service conditions have different rate of heat exchange, in other words marked by different values of rates of heating and cooling. This can be attributed to different automobile suitability to



winter environment that is poorly considered in service thereof and leads to decline in efficiency of motor transport under these conditions [1, 3, 6].

The objective appraisal of automobiles suitability by temperature profile of motors is necessary for decreasing of negative influence on environment by motor-vehicle operation in wintertime.

Researchers associate the higher fuel consumption in winter conditions with deterioration of motors temperature profile [1, 3, 6, 7, 8, 9, 10]. The majority of researchers consider the ambient temperature and wind speed as critical parameters of ambient medium having an impact on thermal state of motors. The basic parameters characterizing the motor temperature profile are steady-state temperature as well as heating and cooling time. The impact of winter environment to period of heating and cooling of engine of different vehicles has a differential nature that is conditioned by various levels of adaptability of these vehicles to severe conditions. The presence of quantitative index of adaptability thereof by temperature profile of engines is necessary for obtaining of possibility for adequate evaluation of vehicle adaptability level.

2. Methodology

2.1. The models of change of engine cooling and heating time

The air speed blowing the car, degree of heat insulation and thermophysical properties of engine determine the rate of engine heat exchange and consequently affect the period of its heating and cooling [6].

Engine cooling period τ_{oxl} after stopping down is determined by thermophysical properties of unit and conditions of cooling process behavior on its surface. However the theoretical determination of engine cooling time is hindered by determination of dependence for irregularity ration of temperature distribution in engine from the cooling conditions on its surface. The differential equation of thermal conductivity for ball may be applied for determination of type of dependence of irregularity ratio of temperature distribution ψ . Solution of this equation allows determining the dependence of irregularity ratio of temperature distribution on Bi number and provide this dependence in the form of adequate model (1):

$$Bi \cdot \psi = b'_1 \cdot \exp\left(\frac{b'_2}{Bi}\right), \quad (1)$$

where Bi – is a Biot number,

b'_1, b'_2 – is a model parameters depending on engine (ball) properties.

Taking into account the formula (1) and that for each engine the heating capacity C , mass M , thermal conductivity λ , determining the amount of l and surface area F are constant – the rate of cooling of individual engine depends only on heat-transfer coefficient α . The model of change of engine cooling time τ_{cool} from initial t_h to final temperature t_k under the influence of ambient temperature t_e , wind speed w and thermal properties of engine is elaborated (2):

$$\tau_{oxl} = \frac{1}{b_1} \exp\left(-\frac{b_2}{\alpha}\right) \cdot \ln \frac{t_h - t_e}{t_k - t_e}, \quad (2)$$

where b_1 – is a model parameter, c^{-1} ;

b_2 – is a model parameter, $W/m^2 \cdot ^\circ C$.

Based on analysis of heat-balance equation the problem of theoretical determination of engine warm-up time τ_{np} , depending on capacity of internal heat source P , ambient temperature, rate of cooling m_{cool} and thermal properties of engine was solved and takes the form (3):

$$\tau_{np} = \frac{730 + 0.5 \cdot (t_k - t_H)}{d_1 \cdot P - d_2 \cdot m_{oxl}} \cdot \ln \left(\frac{t_y - t_k}{t_y - t_H} \right), \quad (3)$$

where d_1 – is a constant of model depending on engine thermal properties, $^\circ C/J$;

d_2 – is a constant of model, $^\circ C$.

The change of engine temperature at a time in the process of warm-up and cooling is described by co-exponential models of adaptability (4) and (5):

$$t_K = t_Y - (t_Y - t_H) \cdot e^{-f(M, m_{oxl})}, \quad (4)$$

$$t_K = t_G - (t_G - t_H) \cdot e^{-f(a, b, w, \tau_{oxl})}. \quad (5)$$

2.2. The characteristics of car adaptability to severe operation conditions

The adaptability coefficient reflecting the change of time for warm-up and cooling under these operating conditions towards its values under standard conditions is applied for characteristics of car adaptability to severe operation conditions. It has been established that the car adaptability coefficients to winter working conditions by engine warm-up time from initial temperature t_H to final t_K is determined from the formula (6):

$$K_{np} = \frac{\tau_{np}^{cm}}{\tau_{np}}, \quad (6)$$

And by the cooling time from the formula (7):

$$K_{oxl} = \frac{\tau_{oxl}}{\tau_{oxl}^{cm}}, \quad (7)$$

where $\tau_{np}^{cm}, \tau_{oxl}^{cm}$ – is a time of engine warm-up and cooling from temperature t_H to temperature t_K under standard conditions, c ;
 τ_{np}, τ_{oxl} – is an actual time of engine warm-up and cooling from temperature t_H to temperature t_K .

Herewith the conditions under which the technically sound vehicle realizes the rating values of own performance index are considered as *standard*.

The applicability of two criterial model of aggregated factor of vehicle adaptability to winter service conditions by the temperature profile of engines which may be called as “adaptability parameter” a is substantiated.

It is proposed to determine the parameter of vehicle adaptability using the following formula:

$$a = \frac{2 \cdot K_{np} \cdot K_{oxl}}{K_{np} + K_{oxl}}. \quad (8)$$

The adaptability parameter varies from 0 to 1. The case $a = 1$ takes place under complete vehicle adaptability to winter service conditions, namely when the warm-up at idle speed and cooling with engine out is performed during the same period that under standard conditions $\tau_{np} \rightarrow \tau_{np}^{cm}$, a $\tau_{oxl} \rightarrow \tau_{oxl}^{cm}$. The car is absolutely poorly adapted for service to actual operating conditions under $a = 0$, if the car engine is not warmed up at all or its warm-up is performed during long time $\tau_{np} \rightarrow \infty$, and cooling time is precious little $\tau_{oxl} \rightarrow 0$. The value of a parameter is also tends to zero if one of the adaptability coefficients included thereto tends toward zero.

2.3. The assessment of cars operating conditions severity

For the purposes of assessment of cars operating conditions severity, for ensuring the comparability of various severe factors of operating conditions the universal severity scale R was applied. The value of H severity index varies from 0 to the largest value $H_{max} = 12R$, corresponding to absence of severity and maximum possible deviation of operating conditions factor from the standard value.

For ease of application in practice the full range of ambient air temperature values is divided into six equal intervals and the range of wind speed values in four intervals: temperate, moderately-severe, sever and highly severe.

For convenience of application in practice the range of car adaptability indicators values may be split into three levels – with low, medium and high adaptability. The specified breakdown may be performed using the standard deviation value σ subject to conformity with allocation of the car adaptability coefficients values to normal law. $\bar{a} \pm 2\sigma$ is accepted as limits for indicators values range, corresponding to confidence coefficient 0.95 (Table 1).

Table 1. Characteristics of car adaptability levels to winter operating conditions by temperature profile of engine

Adaptability level	Range of adaptability coefficient values	Mean value of adaptability coefficient
Low	$(\bar{a} - 2\sigma; \bar{a} - 0.5\sigma]$	$\bar{a} - 1.25\sigma$
Medium	$(\bar{a} - 0.5\sigma; \bar{a} + 0.5\sigma]$	\bar{a}
High	$(\bar{a} + 0.5\sigma; \bar{a} + 2\sigma]$	$\bar{a} + 1.25\sigma$

For conducting of experimental study the approved methods and up-to-date measuring units have been applied, including the multimeter MAS-838 and α -calorimeter with differential thermocouple.

The calibration of engine coolant temperature sensor and calibration of thermocouple have been performed in response to carrying out of preliminary experiments, as well as overall heat retention of thermocouple and mutimeter were determined.

3. The results of applied research

3.1. Methodology of applied research

The Russian-manufactured vehicles Ural 4320, Ural 5557 (YEP 236), Ural 4420 (YEP 238), KpA3 6444, KpA3 255 B1, ZiL 131, ZiL 130, GAZ 53, GAZCA3 3507, GAZ 2705, GAZ 31029, UAZ 31512, VAZ 2106, VAZ 21213, KAvZ 3976 with various degree of engine winterizing have served as a subject of experimental study. The range of ambient temperature study is from 20 above zero to 42 °C, below zero and wind speed –0 to 13 m/s.

For determination of engine temperature measurability by temperature gage value of cooling fluid the experimental data (as exemplified by engine of ZMZ-402) were obtained, which allowed to draw deduction on availability of functional (non-stochastic) relation between non-random variables – value of mean engine surface temperature and its cooling fluid. Therefore the engine coolant temperature is deterministically predicated upon engine medium temperature and may act as a representative temperature for engine generally.

The multimeter was connected to engine temperature sensor for determination of period for engine warm-up after care parking in the open air and whereat the engine starting was performed. The stop watch was switched upon reaching the coolant temperature of 20 °C. The warm-up was performed up to the temperature of 60 °C.

During conducting of experiment for determination of engine cooling time the engine was shut down after continuous operation providing the equal warmup of all minor components. During temperature depression up to 80 – 90 °C the stop watch was stopped. The cooling was performed up to the temperature of 40 °C. The statistical analysis of experimental values of integrated index has allowed to find that the probability of obtained distribution conformance to normal law equals 0.95.

The normal law of distribution was confirmed as a result of statistical analysis of empirical values of adaptability parameters of the vehicles under investigation (Figure 1).

3.2. The allocation of vehicles by adaptability levels

For ease of application in practice the whole range of the vehicles adaptability values parameters was split to three levels – with low, medium and high adaptability, at that $\bar{a} = 0.479$, $\sigma = 0.109$. The

magnitude of adaptability levels difference was established based on statistical check. The allocation of vehicles by adaptability levels is presented in the 'figure 1' and Table 2.

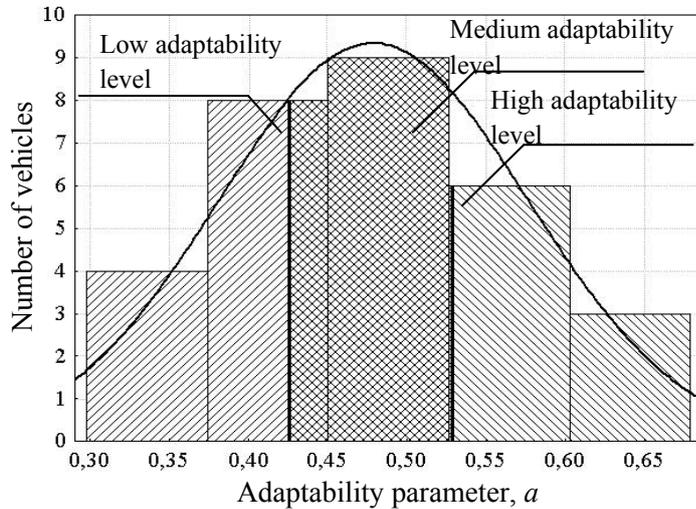


Figure 1. Histogram, distribution curve and vehicles adaptability levels to winter conditions by temperature profile of engines

Table 2. Vehicles allocation by levels of adaptability to winter operating conditions by temperature profile of engine

Level of vehicle adaptability		
Low	Medium	High
GAZ 2705	VAZ 2106	VAZ 2106 ^c
GAZ 53	VAZ 21213	VAZ 21213 ^c
ZiL 130	GAZ 31029	GAZ 2705 ^c
ZiL 131	GAZ 3507	GAZ 31029 ^c
KrAZ 255 B1 ^a	GAZ 53 ^c	GAZ 3507 ^c
KrAZ 6444 ^a	ZiL 130 ^c	KAvZ 3976 ^c
UAZ 31512	ZiL 131 ^c	KrAZ 6444 ^{ac}
Ural 4320	KrAZ 255B1 ^{ac}	UAZ 31512 ^c
Ural 4420 ^a	Ural 4320 ^{ac}	Ural 4420 ^{ac}
Ural 5557 ^b	Ural 5557 ^{bc}	

a – installed with YEP 238 engine
 b – installed with YEP 236 engine
 c – engine insulant applied

Numerical values of integrated index of the vehicle adaptability with high, medium and low adaptability are presented in the Table 3.

Table 3. Numerical values of integrated adaptability index

Level of vehicle adaptability	Severity interval H_V by wind speed, R	Value of integrated index in the severity interval H_i by ambient temperature, R					
		[0 ... 2)	[2 ... 4)	[4 ... 6)	[6 ... 8)	[8 ... 10)	[10 ... 12]
High	[0 ... 3)	0.79	0.71	0.64	0.56	0.48	0.40
	[3 ... 6)	0.75	0.67	0.59	0.51	0.43	0.35
	[6 ... 9)	0.70	0.62	0.54	0.47	0.39	0.31
	[9 ... 12]	0.66	0.58	0.50	0.42	0.34	0.26
Medium	[0 ... 3)	0.64	0.58	0.52	0.46	0.40	0.34
	[3 ... 6)	0.61	0.55	0.49	0.42	0.36	0.30

Level of vehicle adaptability	Severity interval H_V by wind speed, R	Value of integrated index in the severity interval H_t by ambient temperature, R					
		[0 ... 2)	[2 ... 4)	[4 ... 6)	[6 ... 8)	[8 ... 10)	[10 ... 12]
Low	[6 ... 9)	0.57	0.51	0.45	0.39	0.33	0.27
	[9 ... 12]	0.54	0.47	0.41	0.35	0.29	0.23
	[0 ... 3)	0.55	0.49	0.43	0.37	0.31	0.25
	[3 ... 6)	0.48	0.42	0.36	0.30	0.24	0.18
	[6 ... 9)	0.41	0.35	0.29	0.23	0.17	0.11
	[9 ... 12]	0.34	0.28	0.22	0.16	0.10	0.04

The analysis of values of integrated index for vehicles adaptability with different adaptability levels represented in the Table 3, suggests that the higher the adaptability level and lower operating conditions are then the value of adaptability integrated index is closer to one.

3.3. Definition of numerical values of models parameters

The models of cooling time change after engine stoppage and its warm-up at idle speed from the ambient air temperature, wind speed and availability of engine winterization for various car brands and models have been confirmed at the second stage of experimental research. The numerical values of (2) and (3) models parameters are presented in the Table 4.

Table 4. Numerical values of (2) and (3) models parameters

Level of vehicle adaptability	Range of models parameters value variation			
	$\lambda_1 \cdot 10^5, s^{-1}$	$b_2, m^2 \cdot ^\circ C/W$	$d_1 \cdot 10^7, (^\circ C)/J$	$d_2 \cdot 10^{-2}$
High	21.7 ... 36.7	0.8 ... 4.2	5.8 ... 93.0	1.19 ... 3.74
Medium	21.9 ... 56.4	1.6 ... 5.3	5.9 ... 111.5	1.49 ... 3.57
Low	31.4 ... 48.0	1.5 ... 3.8	6.0 ... 57.5	1.29 ... 2.65

For determination of the engine warm-up time at idle speed and engine cooling time after stoppage dependence from ambient air temperature, wind speed and availability of engine winterization for various car brands and models the correlation-regression analysis was conducted. The model verification was performed by Fischer ratio test F and average approximation error $\bar{\epsilon}$. The calculations of specified statistical characteristics have testified that the values of Fischer variance ratio are bigger than tabulated values and the average approximation error fall within the range of 1.4...11.2%, that is evidenced by the model adequacy. The experimental results in graphic form by the example of GAZ 2705 are presented in the Figures 2 – 5.

3.4. The model of generation of adaptability integrated index

Two-factor model of generation of adaptability integrated index was obtained at the subsequent stage:

$$a = 1 - a_1 \cdot h_t - a_2 \cdot h_t \cdot h_w^{0.73} + a_3 \cdot h_t^2 \cdot h_w^{0.73}, \quad (9)$$

where h_t – is severity of operating conditions by ambient air temperature, R ;
 h_w – is severity of operating conditions by wind speed, R ;
 a_1 – is a parameter reflecting the degree of ambient air temperature impact, $^\circ C^{-1}$;
 a_2, a_3 – are the parameters reflecting the degree of wind speed and ambient air temperature impact.

Numerical values of model parameters are presented in the Table 5.

Table 5. Numerical values of model (9) parameters

Level of vehicle adaptability	Range of models parameters value variation		
	$i_1 \cdot 10^{-2}$	$i_2 \cdot 10^{-2}$	$a_3 \cdot 10^{-3}$
High	3.63 8.78	1.65 ... 5.28	2.63 8.02
Medium	4.03 ... 13.33	2.93 ... 6.05	3.60 ... 11.38
Low	7.06 ... 15.02	3.60 ... 7.36	5.82 ... 12.14

According to the findings of investigation the higher severity of operating conditions and lower the level of vehicle adaptability, the more time it needs for engine warm-up at idle speed and the less duration of cooling thereof after shutdown.

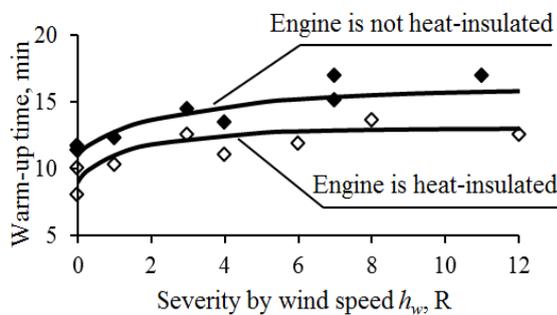


Figure 2. Dependence of time for GAZ 32705 engine warm-up on wind speed under ambient air temperature of minus 30 °C

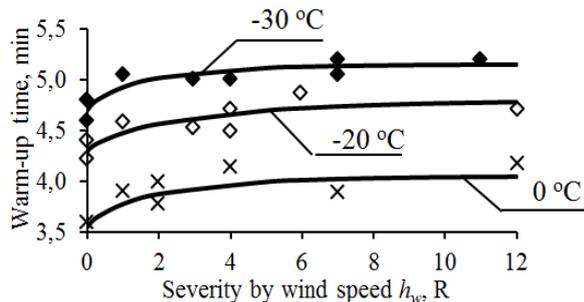


Figure 3. Dependence of time for GAZ 32705 engine warm-up (20 to 60 °C) on air temperature under various wind speed (without heat-insulation of engine)

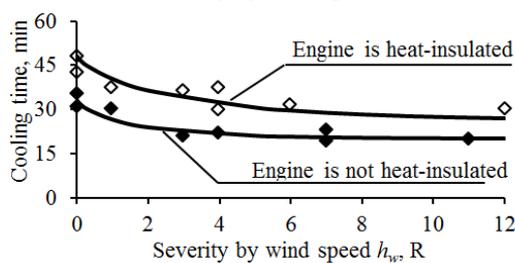


Figure 4. Dependence of time for GAZ 32705 engine cooling (90 to 40 °C) on wind speed at ambient temperature 30 °C below zero

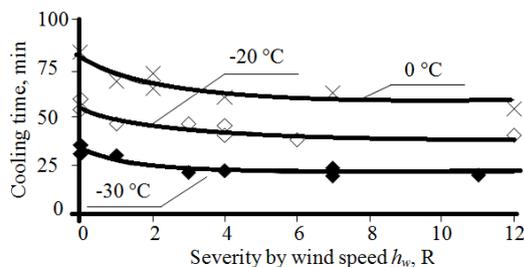


Figure 5. Dependence of time for GAZ 32705 engine cooling from 90 to 40 °C on ambient air temperature under various wind speeds (without heat-insulation of engine)

4. The directions of practical implementation

Numerical values of models parameters established as a result of researches enable developing the following principal directions of practical implementation:

1. Determination of engine cooling under designed conditions of operating conditions severity and level of car adaptability.

2. Determination of rational warm-up period within specified severity conditions under known level of vehicle adaptability.

It is proposed to implement the developed methods for engine temperature maintenance in the range of 40 to 80 °C using the vehicle as standby and in the range of 10 to 60 °C in case of intershift storage of vehicle in isolation from production plant.

The recommendations to operators and industry for improvement of fuel efficiency of vehicles in winter operating conditions are enunciated.

5. Conclusions

In such a way as a result of conducted researches

- The dependency of engine warm-up and cooling time on ambient air temperature and wind speed described by multifactorial mathematical models is established. Numerical values of parameters of established models for vehicles under investigation are defined and adequacy thereof was proved on the basis of experimental research;

- The model of generation of integrated index for vehicle adaptability to winter operating conditions by temperature profile of engines was developed;

- On the basis of experimental data it is found that distribution of integrated index values for adaptability to winter environment by temperature profile of different cars engines is governed by normal law of distribution;

- It is determined that the conformity of the change in integrated index of car adaptability to winter operating conditions by temperature profile of engines is described by the multifactor model, the numerical values of parameters included thereto are also established;

- The method for evaluation of vehicle adaptability to winter operating conditions by temperature profile of engines based on mathematical model of change in engine warm-up and cooling time and implemented on designed program-methodical provision is developed;

- Ecological effect is achieved by means of decrease in fuel consumption that leads to reduction in environmental pollution with toxic agents contained in exhausted gas.

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