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# Some Features of Internal Combustion Engine Conversion from Gasoline to Gas by Taking into Account Valve Mechanism Wear

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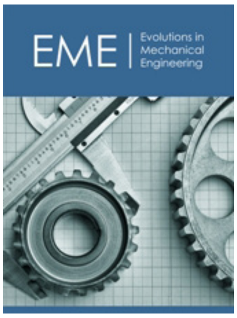

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## Abstract

The main trends in the car gasification are considered. It is shown that after the global automakers lost the interest in the creation and production of gas engines, the development of gas systems continues in the secondary market. A noticeable decrease in the valve train durability due to the valves recession was noted, which can make the conversion of the engine to gas fuel technically inexpedient and economically ineffective. Based on the data obtained, a list of constructive measures was compiled to reduce wear when converting the gasoline engine to gas fuel. A method for calculating the economic efficiency of a gasoline engine operating on gas, taking into account the initial and operating costs, has been developed. It is noted that the transfer of a serial gasoline engine to gas without making changes to the valve train design means an absolutely inevitable decrease in the resource of the valveseat interface. By calculation, it is shown that despite the large difference in price between gasoline and gas, the total economic effect of converting a gasoline engine to gas does not exceed 1520% and in general has a number of serious limitations of an economic and a technical nature. For the first time, it has been shown that any options for unauthorized conversion of car engines to another fuel should be considered, first of all, from the point of view of economic efficiency over the entire service life of the car, and not as private advantages obtained during certain periods of its operation. The results obtained can be used in practice in the development of transport gasification programs, in assessing the real economic efficiency of the use of gas cylinder equipment, as well as in the search for the faults caused by the engine design change if converting it to another fuel.

**Keywords:** Internal combustion engine; Gas fuel; Gas equipment; LPG; Valve recession

## Introduction

The transition of serial gasoline engines to gas motor fuel (liquefied propanebutane or compressed natural gas) has been considered as a promising one for various types of transport for a long time in many countries. The main advantages of such a conversion were previously denoted to be environmental benefits, including more complete combustion of the gasair mixture, a significantly lower cost of gas and a longer durability of the cylinderpiston group. For many decades, the idea of gasification of passenger vehicles has experienced numerous ups and downs, but among the world's automakers, it has not received a large number of supporters [1]. There are quite a few reasons for this and along with purely technical ones, the general gasification of passenger vehicles is also hindered by economic reasons, even despite the obvious savings due to the difference in fuel prices.

### Publication analysis

Not so long ago, liquefied and natural gas were considered environmentally friendly fuels compared to gasoline. However, from the moment carbon dioxide, as a product of combustion, fell into the category of harmful greenhouse gases, liquefied and natural gas were actually recognized as nonenvironmental, which was largely facilitated by the unfolding «electric» revolution in the global automotive. The result of this shift of the mass market sector was the complete and final refusal of world manufacturers of the production of passenger cars with gas engines in favor of electric ones. The first to announce the end of the development of gas topics in the passenger car sector was Honda. Its «environmentally friendly» gaspowered Civic model [2] was removed from the assembly line just a few years after the start of production. Honda was followed by VW, which for a number of years had several gas engines in its production program [3,4], but also announced the complete cessation of their research, development and production. However, the dramatic events that unfolded in the world of mass car production did not affect the field of their operation too much. Over many decades, a fairly stable market for gascylinder equipment (LPG) has formed in some countries with its entire infrastructure, including manufacturers, installers, consumers and regulatory authorities. Inside this world, gascylinder equipment has been developed in its own way, not only reaching the 8th generation in this development, but also gaining the ability to be fully integrated into a serial electronic fuel supply system of any complexity [1,5].

The reasons for the separate development of the LPG market in some countries are far from ecological, they are rather purely economic and even psychological, when the retail price of 1 liter of liquefied gas is a much, sometimes, half as much as gasoline. It turned out that for many consumers, this and only this factor matters in order to encourage them to convert their own car to run on nonstandard (for an engine), but very cheap gas fuel. At the same time, all other features of reequipment are secondary or even unimportant for most consumers [6]. However, serious problems may arise in the further operation of an engine converted to nonstandard fuel. The advantages of gas in durability for the cylinderpiston group are known. When gas is operating, there is no deterioration in lubrication due to the washing off oil by fuel from the cylinder surface and there is no carbon formation on the parts, as is known with gasoline. In such conditions, an engine oil lasts longer and is practically free from degradation when exposed to fuel. At the same time, when the engine is running on gas, accelerated wear of the valve mechanism is revealed in the form of the socalled valve recession, as it shown in Figure 1 [7,8]. Moreover, accelerated wear is shown not only in the connection of the valve with the seat [7], but also the valve rod with the guide [1,8].

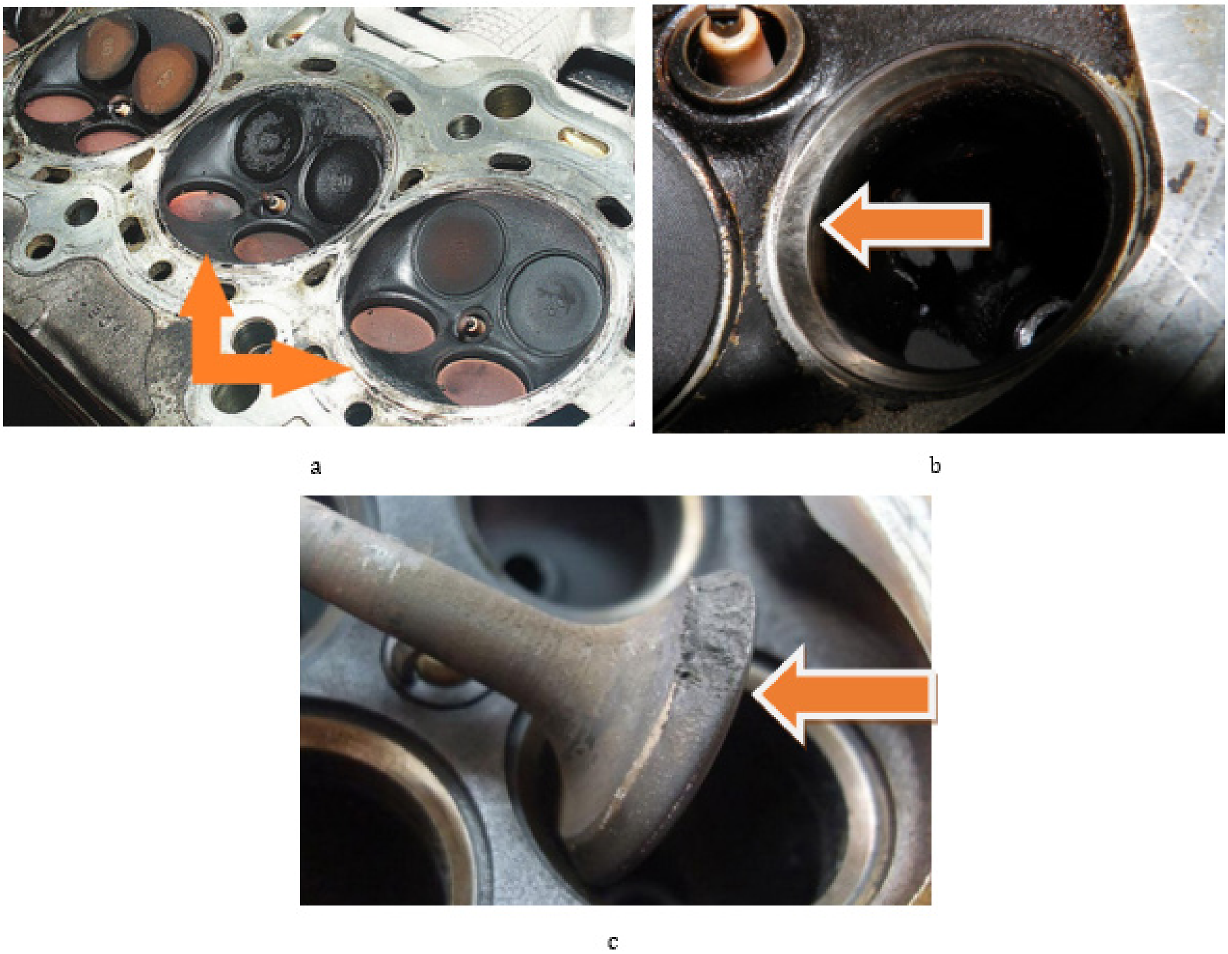

**Figure 1:** Valve recessing during operation on gas (a) occurs due to intense wear of the seat (b) and valve chamfer (c) [7,8].

Not so long ago, it was customary to explain such anomalous wear by some “higher” combustion temperature of the gasair mixture [5,7]. However, detailed studies of the wear process of the «valveseat» pair actually refuted the «temperature» theory and showed the real reasons why a sharp increase in the wear intensity is possible, when the type of fuel is changed from gasoline to gas [1,8,9]. That usually leads to a noticeable limit to the engine's durability compared to its operation on gasoline. The main reason lies in the breakage of the part lubrication during the complete combustion of the gasair mixture, when the lubricant materials are absent in connection between parts (with gasoline it is carbon deposits and gasoline resins). In this case, the rotation and impact of the valve when landing on the seat, necessary with gasoline to remove carbon deposits and resins from the surface (Figure 2), on gas leads to dry friction and rapid wear due to impact loads. And since such wear of the «valveseat» pair, as practice shows, is a key factor in the transfer of an engine from gasoline to gas, the study should be based on the basic laws of this process.

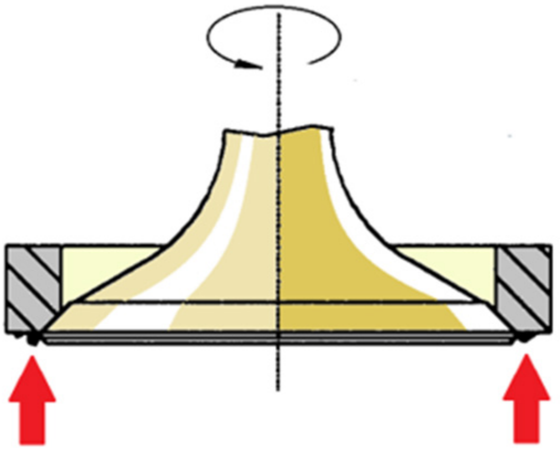

**Figure 2:** When operating on gasoline, the valve rotation and impact on the seat are necessary conditions for displacing carbon deposits from the interface and ensuring its tightness.

At the same time, to convert a gasoline engine to gas, it is not enough just to know the general patterns. When installing LPG equipment on a car, it is also necessary to consider the economic aspects of the conversion, which are directly related to technical issues. However, as the review of publications devoted to gasification shows, a detailed economic analysis is either not carried out at all or is done according to a simplified scheme [9], without taking into account all the necessary operating costs.

## Purpose of the work and problem statement

The purpose of the work is to develop a methodology and obtain quantitative data to assess the economic efficiency and technical feasibility of converting passenger car gasoline engines to natural gas fuel, taking into account various technical limitations and real economic costs. To achieve this, it is necessary to analyze the main patterns of the effect of gas on the wear and durability of components and parts of gasoline engines, as well as to perform a comparative analysis of the technical and economic factors operating in the operation of vehicles of this type.

## Calculation models used to describe the wear process of the "valve seat" friction pair

To obtain quantitative estimates, it is necessary to consider what constitutes and on what the wear of the valve seat interface depends. According to classical concepts, the wear of this pair is determined by the forces that arise now the valve is seated down to the seat and depends on pressure, material properties, roughness, and other parameters [9,10]. This makes it possible to write a semiempirical relationship between the linear intensity (rate) of wear in the form:

$$W = K_1 F_a^k F_y^n F_s^m F_{oil}^q \qquad (1)$$

Formula (1) includes dimensionless factors that affect wear, including the factor characterizing the stress state and actual contact area $F_a$, the fatigue strength factor $F_y$, the surface roughness factor $F_s$ and the factor of the lubricating layer thickness Foil:

$$F_a = f\frac{P}{HB},\ F_y = \xi\frac{P}{\sigma_0},\ F_s = \frac{R_{\max}}{br^{\frac{1}{v}}},\ F_{oil} = \frac{\Delta_{oil}}{\sqrt{R_{a1}^2 + R_{a2}^2}} \qquad (2)$$

where $K_1$ is the experimental coefficient, k, m, n, q are the exponents determined empirically, p is the pressure, HB is the hardness of the material, $\sigma_0$ is the friction endurance limit, f is the friction coefficient, r is the radius of the top of the microroughness; b and v are coefficients of distribution of microroughness heights, ξ is a coefficient depending on the contact form, $R_a$, $R_{max}$ are surface roughness, $\Delta_{oil}$ is the thickness of the lubricating layer on the surface of the mating parts (the equation can include other options).

Considering formulas (2), for the most significant factors, the wear intensity equation can be represented as

$$W = K_2\frac{P^{r+n}}{HB^m \sigma_0^n \Delta_{oil}^q} \qquad (3)$$

However, classical models cannot fully consider all the changes that occur in the interface of parts during the transition from liquid to gaseous fuels. So, in the process of operation, the valve performs a complex loading movement on the surface of a fixed seat, namely impact with slip, which determines the dynamics of the ICE valve train mechanism. Under such conditions, the absence of resins and deposits in the interface can become critical due to the wear of materials in the dry friction mode, accompanied by a corrosion and erosion component.

In the general case, the linear wear rate of the parts of the valve seat pair can be represented as a function of the valve impact (valve seating) and sliding (valve rotation) velocities, which are determined by the corresponding friction path length [11,12]:

$$W = K_2\left(\frac{L_v}{K_u ut}\right)^{n_1}\left(\frac{L_\omega}{K_\omega \omega t}\right)^{n_2}\left(\frac{P}{HB}\right)^{n_3}\left(\frac{R_{a2}}{R_{a1}}\right)^{n_4} \qquad (4)$$

where $L_u$ is the value of the friction path for one cycle of valve operation during its linear movement when sliding on the seat at a speed u, $L_\omega$ is the same when the valve rotates at an angular velocity ω; $k_u$, $k_\omega$ are empirical coefficients; ni, are empirical exponents.

Then, considering dependence (1), the linear wear rate can be represented as a dependence on the rate of linear and angular sliding and loading (impact) when the valve is seated in the seat, the engine operating mode, the valve pressure on the seat, the properties of the pair materials and the thickness of the oil film (soot) between them:

$$W = K_3 u^{m1} \omega^{m2} n^{m3} \delta_{oil}^{m4} \left( \frac{P}{HB} \right)^{m5} \qquad (5)$$

where $m_i$ are empirical exponents, n is the rpm.

In this form, dependence (5) is quite suitable, at least, for a qualitative analysis of the influence of various factors on the wear of the valve seat interface when changing to nonstandard fuel.

## Forecasting the consequences of changing the engine to nonstandard gas fuel

When predicting the change in the resource of specific mass-produced engines associated with the transfer to nonstandard fuel, the number of unknown parameters in formulas (4) and (5) is so large that their determination is very difficult. Therefore, the practical use of formulas that establish the dependence of wear on the design features of engines is not always feasible in an exact quantitative sense. However, the comparative parameters are of interest for practice, including the relationship between the engine durability on gas fuel. Therefore, approximate qualitative and quantitative estimates of the cost of repairs and the economic efficiency of switching a gasoline engine to nonstandard fuel can be made.

So, by definition, the linear wear rate W is the ratio of the wear value to the friction path along which this wear occurred, which can be written as [12]:

$$W = \frac{\delta_\omega + \delta_u}{L_\Sigma} \qquad (6)$$

where $L_\Sigma = L_\omega + L_u$ is the total friction path, $\delta_u$ is the amount of valve wear in one valve operation cycle during its linear movement when sliding on the seat at a speed u, $\delta_\omega$ is the same when the valve rotates at an angular velocity ω.

When the wear of parts is expressed in a linear change in their dimensions, such wear can be represented in a complex way as valve recession [10] $\delta_\Sigma$ in the seat because of wear of both the valve itself and the seat:

$$\delta_\Sigma = W L_\Sigma \qquad (7)$$

whence it follows that the valve recession is proportional not only to the intensity of wear, but also to the path of friction, which is the greater, the greater the speed of rotation and seating of the valve into the seat (Figure 3) [10].

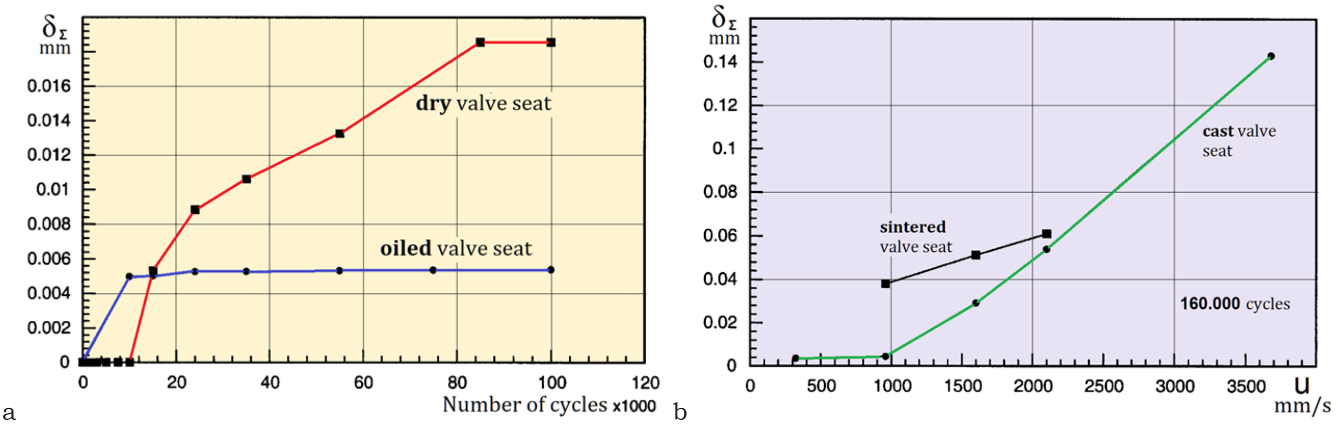

**Figure 3:** Influence of valve impact and sliding in the seat on the valve recession (according to data [10]).

As a result, for the "valve seat" pair under consideration, from formulas (5) and (7), obvious design measures follow to reduce wear when the engine is changed to nonstandard gas fuel [1,2,9]:

A. Decreasing the specific pressure of the valve on the seat [1,2]. It is achieved mainly by a significant (several times) increase in the width of the working chamfer (Figure 4a).

B. Reducing the friction path by eliminating sliding and preventing the rotation of the valve. It is achieved in 2 ways: using the design of a fixed fit of valve keepers and the valve stem in the spring retainer (Figure 4b) and installing 2 concentric valve springs with the opposite winding direction (Figure 4c).

C. Reduction of valve impact speed during landing. It requires the use of other camshaft cam profiles with a smoother fit and possibly, hydraulic compensators.

D. An increase in the hardness of the valve material. It is provided by applying a traditional wear resistant chamfer coating with a special material such as Stellate [13].

E. Increasing the hardness and wear resistance of the seat. It also requires special materials with special properties [14,15].

As shown in [1], the simultaneous and complete satisfaction of all these requirements makes the engine inoperable on gasoline, since the valve seat interface loses its tightness due to a breakage of the self-cleaning of the working contact surface from resins and deposits [10]. At the same time, it is obvious that it is impossible to satisfy these requirements when converting a serial gasoline engine to nonstandard gas fuel without making serious changes to the design of the valve mechanism. Even though the very transfer of a gasoline engine to nonstandard fuel is already a change in the design of the engine. This feature of the engine reequipment turns out to be a key factor in operation since it means an inevitable reduction in the life of the valve to seat interface. This implies an important conclusion for operational practice that the installation of LPG equipment can be performed only on those engine models for which practical experience and data on the real effect of gas fuel on the life of the valve mechanism is known in advance [9]. Otherwise, the owner of the car runs the risk of becoming a test engineer for new technology.

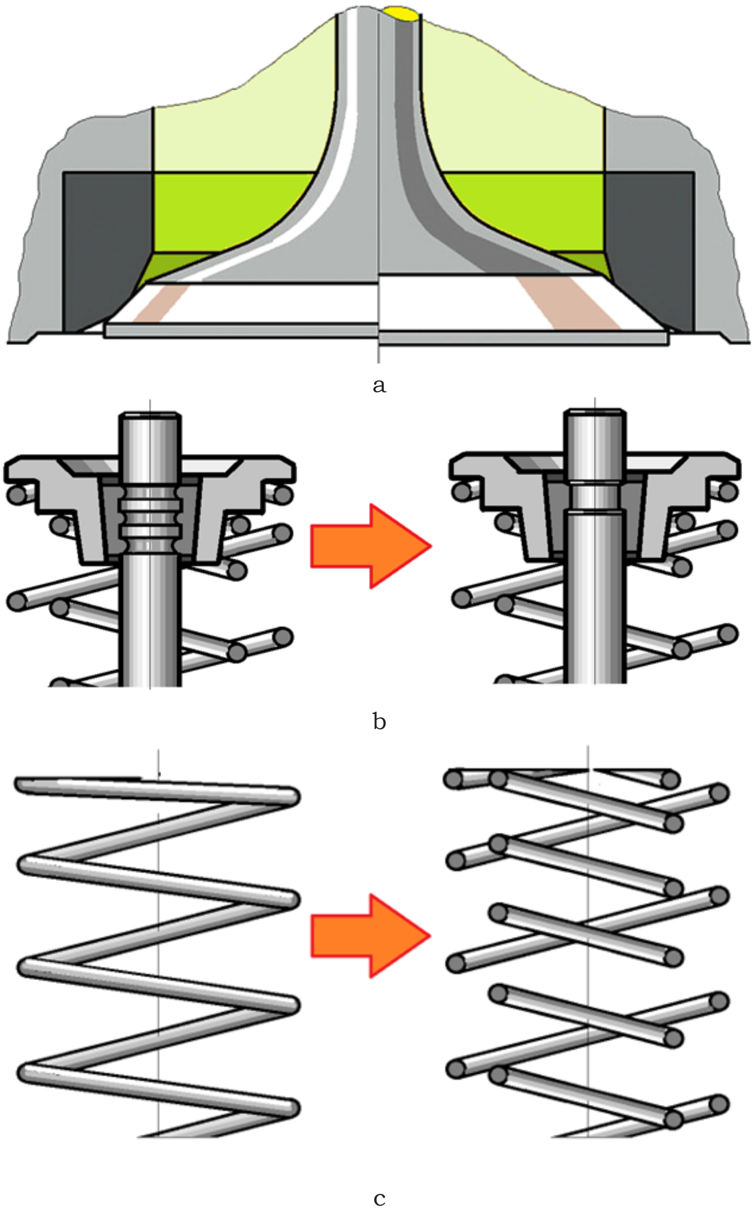

**Figure 4:** Some design measures to reduce wear during the transition to gas fuel, which lie from the design models for the wear of "valve-seat" pairs: a) a wide valve working chamfer; b) valve keepers with a fixed fit; c) concentric springs with the winding opposite direction.

## Methodology for approximate estimation of the economic efficiency of ice transfer from gasoline to gas

If the data on the effect of gas on the life of the valve train is known (and if it is not known, the risk of a car owner suffering serious losses instead of saving may be unacceptably high), the economic efficiency of operating on gas compared to gasoline can be calculated.

a) For this purpose, it is necessary to set some parameters for the car and its engine, including:

b) CLPG is the cost of LPG equipment, its installation and certification.

c) $L_b$ is engine life on gasoline (km).

d) $G_b$ is gasoline consumption (liters / 100 km).

e) $C_b$ is the cost of 1 liter of gasoline.

In addition, it is necessary to set the gas mass flow coefficient g (considering the difference mainly in the density of gas and gasoline) and the price coefficient qc for 1 liter of gas compared to gasoline. In addition, you should also set the relative repair cost $q_{rep}$ of the engine (showing how many times the repair is more expensive than installing LPG) and the relative durability of the engine $l_g$ on gas (showing how much times the engine mileage before repair on gas is less than on gasoline). These quantities can be written like this:

$$g=\frac{G_g}{G_b},\ q_c=\frac{C_g}{C_b},\ q_{rep}=\frac{C_{rep}}{C_{LPG}},\ l_g=\frac{L_g}{L_b} \tag{8}$$

The volume of gasoline $V_b$ and gas Vg consumed for engine durability can be easily calculated using the formulas:

$$V_b=\frac{L_b}{100}G_b,\ V_b=\frac{L_b}{100}G_g \tag{9}$$

The cost of gasoline for the entire service life before repair:

Or

$$C_{L_b}=V_bC_b \tag{10}$$

$$C_{L_b}=\frac{L_bG_bC_b}{100} \tag{11}$$

Accordingly, the cost of gas for the entire service life, considering all additional costs for the installation and operation of LPG, will be equal to:

$$C_{T_g}=C_{LPG}+\frac{C_{rep}}{I_g}+\frac{L_bG_gC_g}{100} \tag{12}$$

Then the relative (concern to gasoline) cost of operating on gas for a service life corresponding to operating on gasoline can be written as:

$$\overline{C}=\frac{C_{L_g}}{C_{L_b}}=100\frac{C_{LPG}+\dfrac{C_{rep}}{I_g}}{L_bG_bC_b}+\frac{G_gC_g}{G_bC_b} \tag{13}$$

or

$$\overline{C}=100\frac{C_{LPG}}{L_bG_bC_b}(1+\frac{q_{rep}}{I_g})+q_cg \tag{14}$$

In formula (14), the second term corresponds to the theoretical economic efficiency of gasification of a gasoline engine without considering additional costs. The first term includes such costs, these are the initial costs for the LPG installation and the possible repair of the valve mechanism during operation. As practice shows, it is the first term that is often not considered, while it largely determines not only the real economic efficiency, but also the technical feasibility of switching the engine to nonstandard fuel.

## Result and Discussion

When performing calculations according to formula (14), the following initial data were taken: gas mass flow rate compared to gasoline g=1,40, price coefficient of a liter of gas compared to gasoline qc=0,50, cost of LPG equipment, its installation and certification $C_{LPG}$=600.00USD, engine life on gasoline $L_b$=150.000 km, gasoline consumption $G_b$=10l/100km, cost of 1 liter of gasoline $C_b$=0,75USD. The calculations were performed with several values of the relative cost of engine repair $q_{rep}$ in the range of 0,53,0 and relative (concern gasoline) engine service life lg in the range of 0,251,0.

The results of calculations using formula (14) are shown in the diagram (Figure 5), where you can see the following characteristic boundaries and areas:

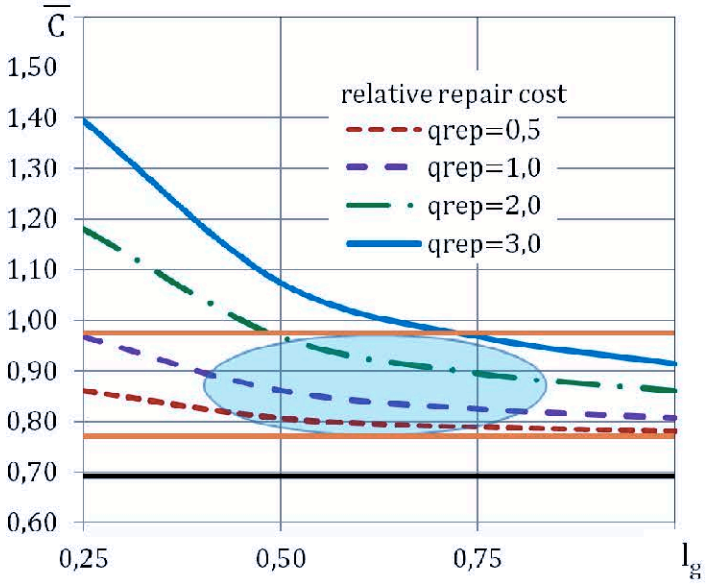

**Figure 5:** The approximate area of economic efficiency of switching the engine to gas fuel at the various values of the relative durability and the relative cost of intermediate repairs.

A. The lower limit of economic efficiency at $\overline{C}$=0,70 corresponds to the maximum theoretical efficiency of the engine running on gas without considering costs. Then $\overline{C}$ = 0,30 (30%) is the fuel savings that the consumer would receive if his initial costs were zero (psychological level $\overline{C}$ = 0,50, i.e. 50% savings that the consumer can see at a filling station in a direct comparison of gas and gasoline prices is not shown because it is not real).

B. The upper limit $\overline{C}$ = 1.0 is the payback limit corresponding to zero economic efficiency. Higher, the transition to gas generally loses its economic meaning, since it physically means a loss (additional, in comparison with gasoline, the cost of operating on gas). In fact, the payback limit is somewhat lower and amounts to $\overline{C}$ = 0.900.95, since the calculations did not consider the loss of time and possible moral damage from an increase in the number of repairs and their cost.

In addition, the area of economic efficiency of converting to gas will be limited to the right by the inevitable reduction of the valve mechanism durability of any gasoline engine running on gas. There is also a limit on the left in terms of the number of repairs or replacements of the cylinder head. For example, if the number of repairs is more than three during the life of the car, we can talk about the technical inexpediency of gasification of this car. As a result, the area of economic efficiency of gasification of a particular car can be shown as an oval (Figure 5). It is easy to see that even a not very expensive version of LPG makes the maximum possible efficiency of switching a car to gas obviously higher than $\overline{C}$ = 0.80. That is, the greatest savings will be only 20% and, at best, will be half as much as follows from a simple comparison of gas and gasoline prices at gas stations. With the growth of the cost of inevitable repairs, the transfer of the engine to nonstandard fuel becomes less and less profitable. For example, if the cost of repairs is twice the cost of the installed LPG, it will already be economically inefficient even with a slight decrease in durability.

An analysis of the spare parts market for some popular cars produced in 2012-2015 showed [16] that most middleclass models have the price of a new cylinder head approximately twice as high as the average cost of LPG installation. Indeed, for some Japanese models, for example, Mazda 6, CX7, Honda Civic, Accord, the price of a new block head is more than three times higher than the LPG installation cost, and for some models of German cars, the difference can be much higher. At the same time, the repair of the cylinder head with the replacement of valve seats, valves and valve guides with new ones often does not lead to the restoration of the condition of a new unit. This is because not everywhere there are workshops with all the necessary high precision machine equipment for this type of repair, and work in such workshops is not always done with high quality [17]. In addition, many parts in modern multivalve cylinder heads determine the significant complexity and cost of repairs. At the same time, many manual operations do not, as a rule, ensure high reliability of the repaired unit in comparison to the new one. In such conditions, neither repair nor replacement of a worn cylinder head with a new one solves all the problems associated with a decreased durability of the valve mechanism when operating on gas. As a result, the LPG installation on the above and similar models may become economically inefficient. And only the most inexpensive models of cars, mostly small class and / or the most popular and widespread, for which there are inexpensive cylinder heads in spare parts, including those made in Asia, make it possible to obtain economic benefits from engine converting on nonstandard fuel. But even in this case, only on condition that the durability of the valve mechanism does not fall by more than half relative to operation on gasoline.

## Conclusion

Any options for unauthorized conversion of automobile engines to nonstandard gas fuel should be considered, first, from the point of view of economic efficiency over the entire vehicle life, but not as private benefits obtained in certain periods of its operation. Despite the large difference in price between gas and gasoline, the total economic effect of converting a gasoline engine to nonstandard gas fuel does not exceed 15-20% for the entire period of vehicle operation. In general, this effect has several serious limitations imposed not only by technical features, but by economic factors. For several car models, especially high-end ones, the apparent benefit from operating on gas can lead to serious losses, which are determined by excessively high repair costs in cases of a noticeable decrease in the life of the engine valve mechanism when operating on nonstandard fuel. According to the results obtained, there are 2 main limitations for unauthorized converting a gasoline engine to gas fuel: the engine durability on gas (no more than 2 times less than gasoline) and the relative cost of engine repairs (no more than 2 times higher than the cost of LPG installation). As a result of the combined action of all factors, the area of permissible, from the conditions of economic efficiency, the use of gas cylinder equipment can be significantly narrowed to inexpensive cars of a small class, as well as common car models for which nonoriginal and / or inexpensive cylinder heads exist and are supplied as spare parts. The conclusion about the economic efficiency (or inefficiency) of converting a specific car model to gas fuel is possible by only considering the existing operating experience and data on the wear pattern of the valve mechanism of a particular engine.

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