Assessment of increased energy efficiency of vehicles
with a rational reduction of engine capacity

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Annotation. Problem. The tendency to reduce Engine displacement, which has emerged in recent years in the global automotive industry, is due to the need to improve the environmental situation and energy efficiency of vehicles. Goal. The aim of the study is to increase the energy efficiency of vehicles by rationally reducing the maximum effective engine capacity. Methodology. In the paper authors used the method of partial accelerations implemented in a mobile registration and measurement complex, which allowed authors to obtain an improved formula for calculating aerodynamic drag. Experimental studies of car aerodynamics were also conducted. Results. In the study presents the results of the authors' research, which made it possible to prove the possibility of reducing the effective engine capacity while maintaining the specified maximum speed and the specified level of indicators of the car dynamic properties. Originality. The relationship between the use of maximum engine capacity and the relative change in the effective specific fuel consumption of a carburetor gasoline engine, with direct injection of gasoline and diesel were determined. Practical value. Calculations performed on the example of the ZAZ-1103 "Slavuta" car showed that a rational reduction in effective engine capacity allows to reduce fuel consumption by 9.5% for carburetor gasoline engine, and for an engine with direct injection of gasoline by 6.7 % and for diesel engines, by 20.3%.

Key words: energy efficiency, vehicle, internal combustion engine, aerodynamic drag, fuel consumption

Introduction

The tendency to reduce the capacity of internal combustion engines, which has been observed in recent years in the global automobile industry, is due to the need to improve the environmental conditions and energy efficiency of vehicles. In the paper authors presents the results of the research, which allowed them to prove the possibility of reducing the capacity of the internal combustion engine while maintaining the specified maximum speed and the specified level of indicators of the vehicles dynamic properties. The relationship between the increase in the degree of use of the nominal internal combustion engine capacity and the change in the effective specific fuel consumption for a carburetor gasoline engine, an engine with direct gasoline injection, and a diesel engine is determined.

Analysis of publications

Energy efficiency is an operational property that characterizes the rational use of engine energy (or another source of mechanical energy) in the process of vehicle operation. The energy consumption of limited and high cross-country vehicles during operation, on paved roads and off-road, was determined in [1]. In the paper [2] it is shown that the energy efficiency of a car is largely determined by the degree of its aerodynamics, which has become an attribute of almost all recognized design solutions. From this, we can come to the disappointing conclusion that aerodynamic drag indicators are decisive in evaluating the energy efficiency of vehicles. The work [3] presents scientific and technical developments dedicated to improving the energy efficiency of vehicles.

In the paper [4] research is devoted to the development of new indicators and criteria of energy efficiency of vehicles. The need for a new approach to energy efficiency assessment is due to the appearance of vehicles with alternative energy sources. In the paper [4], it is proposed to consider not fuel consumption, but energy consumption as indicators of the economy of vehicles.

In the paper [5-7] studies are devoted to the energy efficiency of vehicles using the indicators and criteria proposed in [4], in which vehicles with a mechanical drive, as well as hybrid vehicles and electric vehicles are considered.
At the beginning of the creation of automobile theory [8] by experts in the field of aviation, a calculation formula for aerodynamic drag was proposed

\[ P_w = \frac{C_x}{2} \rho F V_a^2, \quad (1) \]

where \( C_x \) is the coefficient of frontal aerodynamic resistance; \( \rho \) is air density; \( F \) is the middle (frontal area) of the vehicle; \( V_a \) is vehicle speed.

Since that time, when calculating the aerodynamic drag, engineers, taking the value of the index degree at \( V_a \) equals 2, believed that the value of \( C_x \) should be chosen in the calculations depending on the speed of the vehicle. But then, everyone forgot about this and began to accept \( C_x \) at some constant value of speed, spreading the use of the specified value of \( C_x \) throughout the entire speed range of the vehicle.

The well-known German scientist Alfred Jante [9], who studied vehicles in detail in the wind tunnel, recommended determining the \( C_x \) coefficient at an air blowing speed equal to 10 m/s.

The papers [10-15] are devoted to the method of experimental investigation of vehicles aerodynamics. A huge amount of material was accumulated to determine the constant value of \( C_x \) for various vehicles.

The use of the method of partial accelerations, implemented in a mobile registration and measurement complex, allowed the authors of [16] to obtain an improved equation to calculate the force of aerodynamic drag according to equation (1) and with the refined calculation of the force of aerodynamic drag according to equation (2). The ratio between the calculated maximum effective power of the engine, calculated according to the traditional method using equation (1) and the refined one proposed by the authors, has the form

\[ N'_{e_{\text{max}}} = \frac{N_{e_{\text{max}}}}{8} \frac{C_x \rho F V_{a_{\text{max}}}^3}{1 - 0.25 \eta_n} \times \frac{1}{C_x (1 - 0.25 n)} V_{a_{\text{max}}}^n, \quad (4) \]

where \( N_{e_{\text{max}}} \) is the maximum effective engine capacity, which is determined by the traditional calculation of the force of aerodynamic drag according to equation (1); \( N'_{e_{\text{max}}} \) the maximum effective capacity, which is determined by the refined calculation of the force of aerodynamic drag according to equation (2); \( \eta_n^{\text{trans}}, \eta_n^{\text{wheel}} \) are instantaneous efficiency of the transmission and wheels of the vehicle; \( \lambda N \) is the ratio of the effective power of the engine \( n_e \) developed at a given speed \( V_a \) to \( N_{e_{\text{max}}}. \)

By the co-authors of the article Podrigalo M.A. and Tkachenko A.S. were previously obtained equations to determine the maximum power of the engine with the traditional calculation of the force of aerodynamic drag according to equation (1) and with the refined calculation according to equation (2). The results of determining \( A_w \) and \( n \) is shown in Table 1.

<table>
<thead>
<tr>
<th>Car brand</th>
<th>( A_w )</th>
<th>The index of degree ( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAZ-2170 «Priora»</td>
<td>3.60484</td>
<td>0.977252</td>
</tr>
<tr>
<td>VAZ-2110</td>
<td>2.697116</td>
<td>0.877632</td>
</tr>
<tr>
<td>VAZ-2111</td>
<td>11.41</td>
<td>1.298592</td>
</tr>
<tr>
<td>VAZ-2115</td>
<td>8.000009</td>
<td>1.124172</td>
</tr>
<tr>
<td>VAZ-2121</td>
<td>5.401333</td>
<td>0.947272</td>
</tr>
<tr>
<td>ZAZ-1103 «Slavuta»</td>
<td>3.837434</td>
<td>1.151153</td>
</tr>
<tr>
<td>Toyota Corolla</td>
<td>2.385834</td>
<td>0.903548</td>
</tr>
<tr>
<td>Daewoo Lanos</td>
<td>1.822555</td>
<td>0.808</td>
</tr>
<tr>
<td>VAZ-2107</td>
<td>1.897</td>
<td>0.866</td>
</tr>
</tbody>
</table>

Graphs of dependence (3) for 9 passenger car models studied in [17] are presented in Fig. 1.
The ratio between the calculated maximum effective power of the engine, calculated according to the traditional method using equation (1) and the refined one proposed by the authors, has the form

\[
\frac{N_{e,\text{max}}}{N_{e,\text{max}}} = \frac{C_p F p}{8 \cdot V_{a,\text{max}}} \times \frac{1 - \frac{A_{n}}{C_{r} (1 - 0.25n)}}{\eta_{\text{ir}} \cdot \eta_{\text{k}} \cdot \lambda N_{\text{e}}}.
\]  

(4)

where \(N_{e,\text{max}}\) is the maximum effective engine capacity, which is determined by the traditional calculation of the force of aerodynamic drag according to equation (1); \(N_{e,\text{max}}\) the maximum effective engine capacity, which is determined by the refined calculation of the force of aerodynamic drag according to equation (2); \(\eta_{\text{ir}}, \eta_{\text{k}}\) are instantaneous efficiency of the transmission and wheels of the vehicle; \(\lambda N_{\text{e}}\) is the ratio of the effective power of the engine \(n_{e}\) developed at a given speed \(V_{a}\) to \(N_{e,\text{max}}\).

Regardless of whether the calculation of the necessary maximum engine capacity was carried out using the traditional or refined method of determining the force of aerodynamic drag, the actual consumption of engine capacity when the vehicle is moving at maximum speed will be the same. Only the degree of utilization of the maximum effective capacity of the engine will differ. Suppose that in the case of a refined calculation of the maximum effective power of the engine, an increase in the degree of its use at the maximum speed of the vehicle, a decrease in fuel consumption will occur.

**Purpose and Tasks**

The aim of the study is to increase the energy efficiency of vehicles by rationally reducing the maximum effective capacity of the engine.

To achieve the goal, the following tasks must be solved:

- to determine the relationship between the degree of use of the maximum effective engine capacity and the effective specific fuel consumption;
- to evaluate the reduction of fuel consumption of the vehicle with a rational reduction of the maximum effective engine capacity.

**Determination of the relationship between the degree of use of engine capacity and effective partial fuel consumption**

To solve the problem, let us use the load characteristics of carburetor gasoline and diesel engines given in [18]. In Table 2 shows the main indicators of a carburetor engine at throttling [18].

Analysis of the data in Table 2 [18] shows that throttling of a carburetor gasoline engine (CGE) leads to a decrease in the indicator and effective capacity. At the same time, the capacity of mechanical losses remains unchanged, and the specific fuel consumption increases.

Let us enter the notation:

\[
\delta N_{e} = \frac{N_{e} - N_{e,\text{max}}}{N_{e,\text{max}}} \text{ the degree of use maximum effective engine capacity;}
\]  

(5)
\( \delta g_e = \frac{g_e}{g_{\infty}} - \) relative change in the effective specific engine fuel consumption

where \( N_e, g_e \) are the current values of effective capacity and specific fuel consumption; \( g_{\infty} \) the effective specific fuel consumption when realizing the maximum effective capacity of the engine.

In Table 3 shows the calculation of parameters \( \delta N_e \) and \( \delta g_e \) for the CGE presented in the Table 2.

In Figure 2 shows the graph of the dependence of the relative change in the effective specific fuel consumption on the degree of utilization of the maximum effective capacity of the CGE.

Table 2. The main indicators of the carburetor engine during throttling [18].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Throttle position</th>
<th>Throttle position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open on 100%</td>
<td>Gradual reduction of opening</td>
</tr>
<tr>
<td>Intake pressure, kg/cm(^2)</td>
<td>0.88</td>
<td>0.8</td>
</tr>
<tr>
<td>Fuel consumption, kg/h</td>
<td>5.0</td>
<td>4.4</td>
</tr>
<tr>
<td>Capacity, hp:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indicator</td>
<td>23.0</td>
<td>19.7</td>
</tr>
<tr>
<td>Effective</td>
<td>20.8</td>
<td>17.5</td>
</tr>
<tr>
<td>Mechanical losses</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Specific fuel consumption, g/(kWh)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indicated</td>
<td>217</td>
<td>223</td>
</tr>
<tr>
<td>Effective</td>
<td>240</td>
<td>252</td>
</tr>
<tr>
<td>Mechanical efficiency</td>
<td>0.9</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Table 3. Calculation of parameters \( \delta N_e \) and \( \delta g_e \) for CGE.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Throttle position</th>
<th>Throttle position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open on 100%</td>
<td>Gradual reduction of opening</td>
</tr>
<tr>
<td>Effective capacity ( N_e ), kW</td>
<td>15.29</td>
<td>12.87</td>
</tr>
<tr>
<td>Efficient fuel consumption ( g_e )</td>
<td>0.091</td>
<td>0.095</td>
</tr>
<tr>
<td>( \delta N_e )</td>
<td>1.000</td>
<td>0.842</td>
</tr>
<tr>
<td>( \delta g_e )</td>
<td>1.000</td>
<td>1.043</td>
</tr>
</tbody>
</table>

Fig. 2. Dependence of \( g_e (\delta N_e) \) for CBD

To approximate the obtained dependence, it is advisable to use a response function of the form

\[ \delta g^\wedge_e = (\delta N_e)^{n_1}. \] (7)

Using the method of least squares, the optimal regression coefficient \( n_1=0.453 \) was determined.

In Table 4 shows the results of the estimation approximation error.

In Figure 3 shows diesel engine load characteristics at the angular speed of the crankshaft \( \omega_e = 136 \text{ s}^{-1} \) [18].

In Table 5 shows the main parameters of the tractor diesel under different cyclic fuel supplies.

Table 4. Estimation of the approximation error of the dependence \( \delta g_e (\delta N_e) \) for CGE.

<table>
<thead>
<tr>
<th>( \delta N_e )</th>
<th>1.043</th>
<th>1.176</th>
<th>1.429</th>
<th>2.121</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta g_e )</td>
<td>1.081</td>
<td>0.630</td>
<td>0.419</td>
<td>0.207</td>
</tr>
<tr>
<td>( \delta g^\wedge_e )</td>
<td>1.081</td>
<td>1.233</td>
<td>1.482</td>
<td>2.041</td>
</tr>
</tbody>
</table>

Relative error of approximation, %

|                 | 3.6   | 4.8   | 3.7   | -3.8  |

Table 5. The main parameters of a tractor diesel according to different cycle fuel supplies[18].

<table>
<thead>
<tr>
<th>Mode</th>
<th>Cyclic fuel consumption ( G_{\text{cycle}}, \text{ mg/(cycle l)} )</th>
<th>Mean effective pressure ( p_e ), kgf/cm(^2)</th>
<th>Specific effective fuel consumption ( g_e ), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economical (points 2 and 2')</td>
<td>35</td>
<td>5</td>
<td>75</td>
</tr>
<tr>
<td>Powerful (points 4 and 4')</td>
<td>60</td>
<td>6.7</td>
<td>100</td>
</tr>
<tr>
<td>Effective (points 3 and 3')</td>
<td>50</td>
<td>6.4</td>
<td>96</td>
</tr>
</tbody>
</table>
Fig. 3. Diesel engine load characteristics ($\omega_e = 136$ s$^{-1}$) [19]

The results of the processing load characteristics for diesel engine, taken from the work [18], made it possible to obtain the dependence $\delta g_e (\delta N_e)$ (Table 6, Figure 4).

![Graph of diesel engine load characteristics](image)

Table 6 shows the results of estimation of the approximation error. The average error of approximation for 5 points is 5.47%, which is acceptable. Figure 4 shows the dependences of $\delta g_e (\delta N_e)$ and for diesel engine presented in [18].

![Graph of dependencies $\delta g_e (\delta N_e)$](image)

As a result of approximation by three points ($\delta N_e = 1.0; \delta N_e = 0.75; \delta N_e = 0.15$) a response function was obtained, which has the form

$$\hat{\delta g}_e = 0.063^{\delta N_e} \cdot (\delta N_e)^{-1.58} \ (8)$$

For engine with direct gasoline injection, we use the load characteristic obtained by professor A.A. Prokhorenko and associate professor O.P. Kuzmenko.

In Table 7 shows the results of the calculation of the parameter $\delta g_e$ at the angular crankshaft velocity $\omega_e = 419$ s$^{-1}$.

![Graph of dependencies $\delta g_e (\delta N_e)$ for gasoline engine](image)

Table 7. Calculation of the parameter $\delta g_e$ depending on $\delta N_e$ for an engine with direct gasoline injection at $\omega_e = 419$ s$^{-1}$.

| $\delta N_e$ | 0.185 | 0.298 | 0.400 | 0.519 | 0.653 | 0.795 | 0.891 | 0.982 | 1 |
| $\delta g_e$ | 1.557 | 1.227 | 1.107 | 1.009 | 0.960 | 0.916 | 0.906 | 0.888 | 1 |
| $\hat{\delta g}_e$ | 1.463 | 1.268 | 1.161 | 1.074 | 1.002 | 0.945 | 0.913 | 0.887 | 1 |
| Relative error of approximation, % | -6.0 | 3.3 | 4.9 | 6.44 | 4.4 | -3.16 | 0.77 | -0.11 | 0 |
In Figure 5 shows the dependence graph of \( \delta g_e (\delta N_e) \), made according to the calculation results given in Table 7.

The analysis of the course of the curve presented in Figure 5 shows that with \( \delta N_e = 1 \) point of the curve falls out and the curve \( \delta g_e (\delta N_e) \) has a break. And here a partial-linear approximation is proposed, i.e.

\[
\delta g_e = \begin{cases} 
1 & \text{when } \delta N_e = 1; \\
A \cdot (\delta N_e)^{-n} & \text{when } \delta N_e < 1. 
\end{cases}
\]  

(9)

Construction of the response function by selecting one nodal point \( \delta N_e = 0.982 \) (see Table 7) and selecting the degree \( n \) allowed to obtain \( A=0.882 \) and \( n=0.3 \), i.e.

\[
\delta g_e = \begin{cases} 
1 & \text{when } \delta N_e = 1; \\
0.882 \cdot (\delta N_e)^{-0.3} & \text{when } \delta N_e < 1. 
\end{cases}
\]  

(10)

![Graph of dependence \( \delta g_e (\delta N_e) \) for an engine with direct gasoline injection](image)

Calculations of values \( \delta g_e \) for different values of \( \delta N_e \) are given in Table 7. There is also an estimate of the calculation error based on the approximating dependence. Table 7 shows that the maximum error of calculation exceeds 6.44%.

Figure 5 shows the dependence \( \delta g_e (\delta N_e) \) graph for an engine with direct gasoline injection.

A comparative analysis of the course of the \( \delta g_e (\delta N_e) \) curves for different types of internal combustion engines shows (see Tables 3, 6, 7) that for the CGE, a decrease in the degree of utilization of the maximum effective engine capacity \( \delta N_e \) causes an increase in the effective specific fuel consumption \( \delta g_e \). A different situation with diesel engine and the engine with direct gasoline injection. In a diesel engine at \( \delta N_e = 0.3 \cdot 0.96 \). Value \( \delta N_e < 1 \). In an engine with direct gasoline injection, \( \delta N_e < 1 \) at \( \delta g_e = 0.653 \cdot 0.982 \).

**Estimation of fuel consumption reduction with a rational reduction of the maximum effective engine capacity**

Given that with a rational reduction of engine capacity \( N'_{e max} < N_{e max} \), let us determine \( \delta N_e \) from equation (4).

\[
\delta N_e = \frac{N'_{e max}}{N_{e max}} = 1 - C_i \cdot \rho \cdot F \cdot V_{a max} \cdot A_w \cdot \frac{1}{8N_{e max}} \times \\
1 - \frac{A_w \cdot V_{a max}^n}{C_i \cdot (1 - 0.25n)} \times \frac{\eta_{mg} \cdot \eta_{mg}}{\eta_{mg} \cdot \lambda N_e}.
\]  

(11)

Let us evaluate the fuel consumption reduction for the car ZAZ-1103 "Slavuta" with a rational reduction of engine capacity. The initial data for the calculation are given in Table 8. When the car ZAZ-1103 "Slavuta" moves, the power consumption both with installed engine with \( N'_{e max} = 45 \text{ kW} \) and the engine with \( N'_{e max} \) is the same and equal \( N_{e max} \).

But in the second case \( \delta N_e = 1 \), and in the first case \( \delta N_e < 1 \).

**Table 8. Initial data for calculating the reduction of the effective specific fuel consumption of the car ZAZ-1103.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( N_{e max} ), kW</th>
<th>( \rho ), g/m³</th>
<th>( F ), m²</th>
<th>( V_{a max} ), m/s</th>
<th>( A_w ) (m/s)⁰</th>
<th>( C_i )</th>
<th>( n )</th>
<th>( \eta_{mg} )</th>
<th>( \eta_{mg} )</th>
<th>( N_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter values</td>
<td>45</td>
<td>1.225</td>
<td>1.753</td>
<td>40.83</td>
<td>3.837</td>
<td>0.375</td>
<td>1.151</td>
<td>0.85</td>
<td>0.9</td>
<td>0.85</td>
</tr>
</tbody>
</table>

The calculation according to equation (11) showed that for the car ZAZ-1103 "Slavuta" with serial engine capacity \( N'_{e max} = 45 \text{ kW} \), the level of its use is \( \delta N_e = 0.818 \).

In this case, the increase in effective specific fuel consumption (compared to \( \delta N_e = 1 \)) is: \( \delta g_e = 1.095 \) – for CGE; \( \delta g_e = 0.937 \) – for direct injection of gasoline; \( \delta g_e = 0.831 \) – for a diesel engine.
The analysis of the calculation results shows that with a carburetor gasoline engine, a rational reduction of the maximum effective capacity allows to reduce the effective specific fuel consumption by 9.5%. This value is proportional to the absolute fuel consumption (if the effective capacity of the engine is equal). It follows that the expected reduction in fuel consumption will also be 9.5%.

When using engines with direct gasoline injection, on the contrary, a decrease in the maximum effective capacity of the engine will lead to an increase in the effective specific fuel consumption. This increase will amount to $\dot{g}_{fe}^{-1} - 1 = 0.937 - 1 = 0.067$ that is, on 6.7%.

A similar situation occurs to ZAZ-1103 "Slavuta" car with diesel engine. In this case, a decrease in the maximum effective power of the engine will lead to an increase in the effective specific fuel consumption by $\dot{g}_{fe}^{-1} - 1 = 0.831 - 1 = 0.203$ that is, on 20.3%.

Conclusions

The results of well-known scientific investigations allowed us to draw a conclusion about the possibility of a rational reduction of the maximum effective capacity of the engine while maintaining the specified maximum speed and level of dynamic properties of the vehicle.

Since when installing a serial engine and an engine with a reduced value of effective capacity, the realized power is the same, the degree of realization of the maximum capacity is higher in the latter case. The relationship between the degree of use of the maximum engine capacity and the relative change in the effective specific fuel consumption of a carbureted gasoline engine with direct injection of gasoline and diesel is determined.

Calculations performed on the example of the car ZAZ-1103 "Slavuta" showed that a rational reduction of the effective capacity allows for a 9.5% reduction in fuel consumption for CGE, and for an engine with direct injection of gasoline and diesel, this leads to an increase in fuel consumption by 6.7% and 20.3%, respectively.

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Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Оцінка підвищення енергоефективності автомобілів при раціональному зниженні потужності двигунів

Анотація. проблема. Тенденція до зменшення робочого об’єму двигунів внутрішнього згоряння, що напівсталися останніми роками у світовому автомобілебудуванні, обумовлена необхідністю покращення екологічної обстановки та енергоефективності автомобільного транспорту. Мета. Метою дослідження є підвищення енергоефективності автомобілів шляхом раціонального зменшення...
максимальної ефективної потужності двигуна. Методологія. У роботі використано метод парциальних прикрокен, реалізований в мобільному реєстраційно-вимірювальному комплексі, що дозволило авторам отримати удосконалену формулу для розрахунку сили аеродинамічного опору. А також проведені експериментальні дослідження аеродинаміки автомобіля. Результати. У статті наведено результати досліджень авторів, що дозволили довести можливість зменшення потужності ДВЗ при збереженні заданої максимальної швидкості та заданого рівня показників динамічних властивостей автомобілів. Оригінальність. Визначено взаємозв'язок між ступенем використання максимальної потужності двигуна та відносною зміною ефективної питомої витрати палива карбюраторного бензинового двигуна з безпосереднім упорскуванням бензину та дизеля. Практична цінність. Розрахунки показали, що відносна зміна ефективної питомої витрати двигуна для КБД на 9,5% зменшує загальну витрату палива, а для двигуна з безпосереднім упорскуванням бензину та дизеля, це призводить до збільшення витрати палива на 6,7% та 20,3% відповідно.

Ключові слова: енергоефективність, автомобіль, двигун внутрішнього згоряння, аеродинамічний опір, витрата палива.

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