Development of a technique of gear ratios optimization with the aim of simultaneously increasing the vehicle dynamic, fuel efficiency and reducing emissions

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Abstract. The article deals with the problem of choosing of rational gear ratios with the aim of simultaneously increasing the vehicle dynamic, fuel efficiency and reducing emissions. A review of known approaches to the optimization of vehicle gear ratios is conducted. Russian Federation regulations requirements regarding vehicle dynamic are analyzed. The characteristics of an internal combustion engine, such as a mechanical and fuel map are obtained experimentally. The numbers of gears to be optimized are chosen reasonably. The methodology of the fuel usage calculating according to driving test in the standardized cycles was developed and demonstrated.

1. Introduction

Among the performance properties (PP) of vehicles, the dynamic properties and fuel efficiency are recognized as the most significant. It largely determines the effectiveness of vehicle and forms the consumer appeal and competitiveness. In recent years, the number of harmful substances (HS) in exhaust gases, emitted into the atmosphere during motion of vehicle equipped with an internal combustion engine (ICE), has acquired considerable importance. The values of emissions are standardized and listed in UNECE Regulations No. 83 [1] and No. 49 [2]. If these Rules are not met, vehicles are denied access to the sales market.

There are many possible ways simultaneously increasing of dynamic properties, fuel efficiency and at the same time reducing emissions vehicles. This article deals with optimization of vehicle gear ratios. This option is less expensive in comparison with engine upgrading or weight reduction, and also affects all three specified vehicle technical characteristics. The results of investigation can also be useful as basic data for algorithms of switching of automatic transmission gives additional value for work.

To determine the best approach to improving the vehicle performance indicators mentioned above, a review of existing research in this field was carried out. The works aimed at finding of optimum gear ratios, optimum algorithms of gear shift in automatic transmission reducing fuel or consumption of energy of vehicles were the center.

The aim of the article [3] was to search for optimal gear ratios to minimize fuel consumption and improve dynamic performance. Experimentally obtained detailed characteristics of the diesel engine were used in the investigation. Weight coefficients were used to combine the two optimization goals.
As a result, the Pareto curve was built to analyze the fuel efficiency and driving time. Since the subject of the study was a 30-ton quarry truck, the article considered only one cycle of its movement, in which there was no effect of stopping at traffic lights and traffic congestion, limiting the speed of traffic. In the article [4], specialists of General Motors conducted a study aimed at optimizing some parameters of automatic transmission, such as the number of gears, and the ratio of the top and first gears in order to reduce fuel consumption. An increasing the number of gears above eight was found impractical. Further increasing the number of gears does not lead to significant fuel economy. The minimum fuel consumption was achieved with number of gears of automatic transmission equals 10. In the article [5], optimization of transmission gear ratios was considered to minimize fuel consumption on a given route with specified macro profile parameters. The optimization was carried out using an algorithm based on solving specially obtained differential equations. To simplify the optimization algorithm the fuel consumption in the task was replaced by the energy consumption. The way of optimizing the gear ratios of a two-stage gearbox of a car, equipped with an electric motor as an engine, was shown in the presentation [6]. The optimization goals were the increase of dynamic indicators (acceleration time up to 100 km/h), as well as minimization of fuel consumption. For the second indicator, three standardized cycles were analyzed: NYCC, NEDC, HWFET. To find the optimal solution for two mutually opposite goals, energy consumption graphs as well as the acceleration time were plotted for each cycle, depending on the range of gear ratios of the two-stage reducer. The presented method is simple enough to implement and is usable for discussion with manufacturers. Particular interest from the point of view of the applied approaches to solving optimization problems is in the work [7], where the problem of minimizing the power consumption of a hybrid vehicle engine was solved due to the optimal energy management strategy. In the article [8] the problem of optimizing the gear ratios of the 6-speed gearbox was solved in order to reduce fuel consumption only. The Taguchi engineering method (TQEM) combining mathematical tools and tools for working with statistics was used in the experimental studies. In the work [9] simultaneous improvement of fuel efficiency and dynamic properties was achieved by developing several scenarios of optimal gear shifting in automatic transmission. The method of gear shift based on stochastic dynamic programming was found to be the most effective, which allows using it in real time mode. In the article [10] the problem of undesirable or superfluous switching of automatic transmissions, which is a consequence of that switching algorithms have no possibility to predict a road situation, was solved. To solve this problem, a gear shift prediction algorithm, with a route data from the navigation system and an additional data of the vehicle state, was used. The article [11] describes the activities that were carried out to increase the dynamics, reduce emissions of harmful substances and improve the fuel economy of the SUV. The first action to improve these indicators was the modernization of the ICE, namely the injection system, turbocharger and recirculation of exhaust gas. The second action was the selection of gear ratios for the purpose of satisfying predetermined indicators of dynamic properties, fuel efficiency and emissions of harmful substances. The NEDC and UDDS cycles were considered. It should be noted that only the first, fifth and main gears were considered in the optimization.

According to the conducted researches it is possible to make a conclusion that the topic of searching for the optimal gear ratios is quite well studied. The problems of the present study are closely connected with the problems of the work [11] with the exception that the goal of the work [11] was the satisfaction of given indicators, and not the search for the most effective gear ratios. To solve the problem of simultaneous reduction of fuel consumption and increase of the dynamics the approaches described in article [6] considering six gears instead of two and also adding another optimization goal for reducing the emissions can be found appropriate. Taking into account the abovementioned, the distinguishing feature of this work is the extension of the optimization range of the gear ratios for six gears in conjunction with the emissions as an additional optimization objective.

To carry out the optimization of the transmission gear ratios, the following tasks must be solved:

- Preparation of input (initial) data, including the results of experimental studies.
- Analysis of regulations of the Russian Federation (RF) in relation to the requirements to the vehicle dynamics. Analytical calculation of the properties of vehicle dynamics. Definition of the optimization range
- Calculation of fuel economy properties for vehicle movement according to standardized cycles
- Verification and validation of calculation results using comparison with experiment data.
- Development of an algorithm and a program of the optimal gear ratios calculating. Optimization of gear ratios.

The article will describe in details the solution of problems 1-4. Verification and validation of calculations, as well as the development of an algorithm and a program of optimal gear ratios calculating, are planned at the next stages of the study.

2. Preparation of the initial data

The main part of the parameters for making calculations was determined by reference data or by information from the component manufacturer. These parameters include the current values of gear ratios, the transmission efficiency, the dynamic radius of the wheel, the cross-sectional area of the car and others. Using experimental studies, the specified ICE data were determined: the mechanical map - the dependence of the torque on the engine's rotational speed and on the fuel supply, the fuel map - the dependence of the specific fuel consumtion on the engine's speed and on the load. The obtained data are shown in Figure 1.

Numerical values on the ordinate axis on the graphs are absent and this is due to the fact that this information is a commercial secret of the engine manufacturer. It should also be noted that for the prediction of harmful substances emissions values, also experimental data of ICE tests, namely the dependence of emission specific values on engine speed and its load is needed. At the moment, such tests have not been carried out, but this is planned for the subsequent stages of the study.

![Figure 1. Engine dynamic tests data: a) a mechanical map, b) a fuel map](image)

3. Analysis of single indicators of vehicle dynamics

In the Russian Federation, the next indicators of the vehicle dynamic properties are standardized by the technical regulations:

- Maximum speed. The test conditions are standardized by GOST 22576-90 [12]. The maximum permissible values are specified in GOST R 52280-2004 [13].
- Acceleration time on a specified distance (GOST 22576-90).
- Acceleration time to the set speed (GOST 22576-90).
- Speed characteristic "acceleration - run-out" (acceleration on the distance of 2000 m and deceleration (engine braking) to a stop - GOST 22576-90).
- Acceleration on the gear, providing the maximum speed (GOST 22576-90).
- Maximum slope (GOST 52280-2004).
- Speed on the long slope (GOST R 51734-2001 [14]).

For all these indicators, only the experimental determination conditions are normalized, and only for the first, sixth and seventh the permissible values are standardized. The first indicator sets the optimization limits for the top gear of the transmission or, taking into account the capabilities of the ICE, uniquely determines its value. The sixth and seventh indicators uniquely determine the minimum value of the first gear ratio and a gear on which the vehicle can move at a speed of at least 20 km/h on a 12% slope (most often the I or II gear). It should be noted that the last two indicators are relevant only for vehicles that are operated in mountainous terrain. All of the abovementioned indicators of vehicle dynamic properties can be determined using the formulas of the classical theory of the automobile [15]. Thus, it is possible to tell with confidence that it is desirable to optimize gear ratios 2 (in the limited range), 3, 4 and 5 numbers of transfer in case of the automobile gearbox with six speeds. If there is direct gear in the transmission (most often at the IV gear), this further narrows the optimization range, since direct transmission has a higher efficiency and a lower noise level. So the ratio of the direct gear can be changed only by correcting the main gear ratio value.

To take into consideration the dynamics of vehicle in optimization of the gear ratios, it is necessary to be guided by the conditions of determination of the parameter "acceleration time to the set speed" according GOST 22576-90.

4. Calculation of fuel economy for vehicle movement according to standardized cycles

For assessing the fuel efficiency of cars according GOST R 54810-2011 [16], two types of driving cycles have been established: highway and urban.

Simulation of the vehicle's movement is performed in accordance with technological (operational) maps and traffic patterns in the highway cycle (Qs hc) and urban cycle (Qs uc) on a straight and horizontal road.

The main provisions (assumptions) of the methodology are formulated in the following form:
- a continuous process of a car motion can be represented by a combination of individual components of the movement: acceleration from zero and non zero velocity; constant speed; engine braking; motion when the engine is idling;
- dynamic motion of a car (the acceleration is not constant) can be represented by a combination of modes with pre-determined variations in the speed of motion, within which the acceleration remains constant;
- partial load characteristics of the engine can be used in calculation of the fuel economy properties of the car.

The adopted assumptions make it possible to substantially simplify the problem of calculating fuel consumption for an uneven motion. Modeling of the vehicle motion when the engine is running at partial loads allows to differentiate the processes of unsteady motion and calculate the actual characteristics of fuel economy for small values speed change intervals. The made assumptions are expected to provide accuracy in fuel consumption calculating, not only in motion according standardized cycles, but also in motion along a real route the structure of which is determined by the specified components.

In simulation of motion in driving cycles, all the requirements of regulatory documents regarding the choice of gears for acceleration and motion, fuel supply during acceleration, requirements for possible speed deviations from the set value are taken into account.

The scheme of the highway cycle consists of next pieces:
- acceleration starting from the constant non zero velocity;
- constant speed motion;
- engine braking.

The scheme of the urban cycle is distinguished by the presence of next types of motion:
- acceleration starting from zero speed;
- service braking with deceleration of 1 m/sec²;
- engine work in an idling mode.

The urban cycle is fundamentally different from the highway cycle by the presence of acceleration starting from zero speed. As acceleration is started from the lowest transfer and carries out in the rated power of the engine, acceleration of the vehicle can't remain constant, and the fuel consumption should be determined according to the specified circumstances. The second feature of the cycle is the presence of service braking up to vehicle stopping and the engine is idle. According GOST 54810 - 2011, service braking is performed on a given distance (the path length is determined from the average deceleration of 1 m/sec²) with the gear engaged using the service brakes. When the vehicle brakes to a full stop, the gear should be switched to the neutral position when the minimum speed is reached.

Description of the standardized cycles does not determine either the distance or the time of accelerations.

Uncertainty of the requirements of regulatory documents with respect to the parameters of motion during acceleration require additional computational operations that allow us to establish the dependencies or graphs of the characteristics (functions) \( a = f (V) \) and \( V = f (S) \) obtained under the conditions of tests with full fuel supply.

As a result of preliminary calculations, it was found that the accelerations according requirements of regulatory documents with respect to the parameters of motion and on gear number, used at the beginning and end of the acceleration paths, vary insignificantly, by approximately 8...12%. This circumstance allowed us to determine the mean values of the accelerations for each of the acceleration distances and in subsequently determine the fuel consumption for the uniformly accelerated motion.

From this moment, the assumption about the linearity of the acceleration characteristics is introduced, due to insignificant variations of the acceleration values at each moment of time. The above assumption substantially simplifies the task of calculating of fuel consumption at acceleration distances due to the possibility of using the fuel characteristics of vehicle acceleration. To determine the fuel consumption on the sections of motion at a constant speed, the fuel consumption characteristics of the steady-state traffic for the respective gears are determined by the cycle description. Fuel consumption characteristics link the vehicle's design parameters and motion conditions. The graph of the characteristic represents the dependence of the fuel consumption \( Q_s \) on the steady-state velocity \( V = \text{const} \) on roads with different values of the drag coefficient \( \psi \) (figure 2). Assuming that the car is moving without slipping driving wheels, evenly, without acceleration \( (a = 0) \) and the power expended for acceleration is equal to \( P_a = 0 \), the fuel consumption is calculated by formula [15]:

\[
Q_s = \frac{g_{el}(P_{\Psi} + P_v)}{360 \rho V \eta_k \eta_{tr}},
\]

where \( g \) – specific fuel consumption; \( \rho \) – fuel density; \( \eta_k \) – efficiency of transmission; \( k \) – coefficient of correction of power and torque values obtained using bench tests; \( V \) – velocity; \( P_{\Psi}, P_v \) – respectively, the powers expended to overcome the resistance of movement and air resistance.

The fuel consumption characteristics of acceleration \( Q_s = f (V, \psi) \), fig. 2, can be calculated using the fuel consumption characteristic of steady motion. Assuming if the fuel consumption is calculated when driving on the road with a constant value of the coefficient \( \psi \) (with acceleration \( a = 0 \)), then the motion along the road with the drag coefficient \( \psi > \psi \), other things being equal, can be considered as uniformly accelerated, at which the resistance to acceleration will be equal to:

\[
F_{\Delta} = \delta m \alpha \Delta a = F_{\psi 2} - F_{\psi 1},
\]
where $F_a$ – acceleration resistance force; $\delta$ – coefficient of acceleration of rotating masses; $a$ – vehicle acceleration; $F_\psi 1$, $F_\psi 2$ – forces of resistance to movement, respectively, for resistance coefficients $\psi 1$ and $\psi 2$.

If the characteristic of the fuel flow rate is specified by the drag coefficient $\psi$, $Q_s = f (V, \psi)$ then the value of the constant acceleration of a car whose engine is running in full power mode can be determined from expression:

$$a_{an} = \frac{F_\psi 0 - F_\psi 1}{\delta m},$$  \hspace{1cm} (3)

where $a_{an}$ – vehicle acceleration at motion on the road with a drag coefficient $\psi$.

The resistance force at uniformly accelerated motion on the acceleration distances is determined according expression:

$$F_\psi = F_a + F_\psi = \delta m, a + F_{\psi},$$  \hspace{1cm} (4)

where $F_\psi I$ – resistance force at uniformly accelerated motion on the acceleration distances of the highway cycle; $a$ – average value of the acceleration on the acceleration distance; $F_\psi$ – resistance force at uniform movement of the vehicle on the road with a drag coefficient $\psi$; $m$ – gross vehicle mass.

To calculate the fuel consumption in the acceleration distances of the cycles, the fuel consumption characteristics of the vehicle $Q_s = f (V, a)$ for the average acceleration values $a_i$, in the acceleration distances should be determined. The abscissa (speed) within each part of the acceleration must be divided into sufficiently small intervals $\Delta V_i$ such that the initial $\Delta V_i -1$ and the final value $\Delta V_i$ of the velocity within the selected segment ensure minimum deviations from the mean value of the speed of the segment: The distance passed by the vehicle during the accelerating time provided that acceleration constant, and average speed in each selected segment in the accelerating section equal to:

$$V_{i,av} = \frac{V_i + V_{i-1}}{2},$$  \hspace{1cm} (5)

where $V_{i,av}$ – average speed of the vehicle within the selected segment; $V_i, V_{i-1}$ – respectively, the initial and final values of the velocities of the selected segments.

The time for overcoming the selected segments is defined as

$$\Delta t_i = \frac{V_{i-1} - V_i}{a_i},$$  \hspace{1cm} (6)

where $\Delta t_i$ – time for overcoming the selected segment; $a_i$ – acceleration.

The distance traveled by a car within the selected segment of velocities, taking into account expressions (5) and (6), is calculated by formula:

$$\Delta S_i = V_{i,av} \Delta t_i = \frac{V_i^2 - V_{i-1}^2}{2a_i},$$  \hspace{1cm} (7)

where $\Delta S_i$ - distance traveled by a car within the selected segment.

The fuel volume $Q_i$ (l) consumed on the segment $V_i - V_{i-1}$ is determined according expression:

$$Q_i = \frac{\Delta S_i}{100} \frac{Q_{eq}}{a_{eq}},$$  \hspace{1cm} (8)

where $Q_{eq}$ – fuel consumption on the segment of the speed change $V_i - V_{i-1}$; $Q_s$ – volume of fuel consumed on a segment $V_i - V_{i-1}$.

The volume of fuel consumed at the i-th acceleration section can be calculated by the formula:

$$Q_{acc,i} = \sum_{i=1}^{k} \frac{Q_{eq} \Delta S_i}{100} = \frac{1}{200a_k} \sum_{i=1}^{k} Q_{eq}(V_i - V_{i-1}),$$  \hspace{1cm} (9)

where $Q_{eq}$ – fuel volume consumed in the acceleration section; $k$ – the number of intervals (segments) in the range of change in speed during acceleration; $V_i$ – initial speed of the acceleration section; $V_{i-1}$ – final speed of the acceleration section.

When calculating amount of fuel consumed by a vehicle on sections of a driving cycle with engine braking, the section is divided into segments $\Delta S$ such that within the segment the car's deceleration can be considered as constant. Taking into account the expression for the average speed of movement, the average angular speed of the engine's crankshaft can be set for each segment

$$\omega_{el} = \frac{V_{i,av} \omega_{tr}}{r_k},$$  \hspace{1cm} (10)
where \( w_c \) - average angular rotation frequency of a crankshaft; \( V_{\text{av}} \) - average speed; \( u_c \) – transmission ratio; \( r \) – rolling radius of a wheel.

The load power of the engine \( P_c \) at motion with engine braking is determined in accordance with expression:

\[
P_{c1} = \frac{P_{\text{sl}}+P_{\text{sl}}}{\eta_{\text{typ}}} + P_{\text{fr}},
\]

where \( P_{\text{sl}}, P_{\text{fr}} \) – respectively, the power expended to overcome the resistance of the road and resistance of the air; \( P_c \) – power expended to overcome the friction in the engine.

In the event that the friction torque \( T_f \) in the engine is known at a minimum angular velocity, the value of the motor power loss \( P_{\text{fr}} \) can be calculated at any travel speed.

\[
P_{\text{fr}} = \frac{(T_{\text{fr,0}}+b_{\text{fr}}u_{\text{fr}}V_{\text{av}})u_{\text{fr}}V_{\text{av}}}{1000\eta_k},
\]

where \( b \) - coefficient of torque accounting the change in the crankshaft rotation speed.

In the case the component \( P_{\text{fr}} \) of the equation (11) can not be determined, the engine load power in the engine braking mode is determined taking into account the first term.

Overall fuel consumption during engine braking in the section \( \Delta S \) is determined by means of the known dependence and the total power loss in this case is equal to the power of losses in the engine.

\[
Q_{\text{sl}} = \frac{8\eta_{\text{fr}}}{36V_{\text{av}}p_t k_{\text{fr}}}
\]

The amount of fuel consumed in the deceleration area is determined in accordance with expression (9).

The amount of fuel consumed when the engine is idling \( Q_{\text{im}} \) can be determined using expression

\[
Q_{\text{im}} = \frac{G_t}{\rho_t}
\]

where \( G_t \) – hourly fuel consumption; \( t \) – the time of engine idling.

The engine operating time in this mode of motion must be determined taking into account the operating card of the cycle.

The fuel consumption in the areas of service braking is determined taking into account the features of using the service brake system. When braking using the service braking system, the engine operates in idling mode. Therefore, to calculate the fuel consumption in this mode of motion according formula (14), it is sufficient to determine the service braking time according the operating card of the cycle.

The total fuel consumption in the cycle is composed of all components of the cycle scheme: acceleration, constant speed, engine braking, engine idling and service braking.

For example, the fuel consumption \( Q_h \) in the highway cycle, taking into account all the components of the motion, is given by

\[
Q_h = \sum_{i=1}^{3} \sum_{j=1}^{k} \frac{Q_{\text{sl}}\Delta S_i}{100} + \sum_{j=1}^{m} \sum_{k=1}^{3} \frac{Q_{\text{sl}}\Delta S_j}{100} + \sum_{e=1}^{6} \frac{Q_{\text{sl}}\Delta S_e}{100},
\]

where \( i \) – number of acceleration sections; \( j \) – number of engine braking sections; \( m \) – number of selected segments in the engine braking section; \( e \) – number of traffic sections with constant speed; \( Se \) – length of a section of motion with constant speed. The motion schemes and graphs of the current fuel consumption calculated according to the above mentioned formulas, respectively for the highway and urban cycles are shown in figures 3-6.
5. Conclusions

- The analysis of the works in the field of transmission gear ratios optimization is carried out. The most rational approaches to the solution of the problem of transmission gear ratios optimization was identified from the point of view of a simultaneous increasing of vehicle dynamics, reducing of fuel consumption and reducing of emissions of harmful substances.

- The initial data were prepared to perform the calculations. During the experiment on the dynamometer bench, a mechanical and fuel map of the ICE were obtained. The dependence of the specific values of the emissions on the speed of internal combustion engine and the load on the engine is expected to be obtained at the next stages of the study.

- The analysis of the current regulations of the Russian Federation in relation to the requirements to the indicators of vehicle dynamics properties is carried out. The numbers of gears are determined, the ratio of which is uniquely determined by the conditions for the fulfilment of the regulations. Calculation methods for single indicators of the properties of vehicle dynamics are determined.

- A methodology for the analytical calculation of fuel consumption in motion according standardized cycles has been developed and demonstrated. The obtained results of calculation according developed technique are shown.

- The next steps that are planned to be done to complete the study are verification and validation of the calculation results by comparisons with field tests results and developing an algorithm and a program for calculating the optimal gear ratios of the vehicle.
This research was conducted with the financial support from Ministry of Education and Science of the Russian Federation in the frame of the complex project “The establishment of the high-tech manufacturing of safe and export-oriented GAZ vehicles with autonomous control systems and the possibility of integration with the electric platform on the base of components of Russian production” under the contract №03.G25.31.0270 from 29.05.2017 (Governmental Regulation №218 from 09.04.2010).

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