EXPERIMENT AND THEORY: DISTRIBUTION OF CHARACTERISTICS OF CAR MOTION

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ABSTRACT

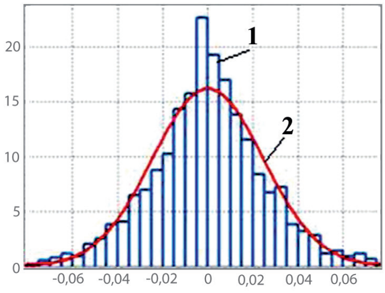
The main factor that forms the perturbation, acting on the car in operating conditions, is the speed of movement. Analytical studies of operational properties and reliability indicators are based on the characteristics of traffic – distribution of runs and speed, in some cases obsolete, or incomplete and not correlated with the characteristics of the macro profile of traffic routes. The data on research of characteristics of the macro profile of country roads of the central Russia are given, their classification is offered. Stationary arrays of random values of relative mileages are allocated and the approximation of random speed distributions by analytic dependences is performed. The obtained results allow to simulate the car movement at early stages of design works and to improve the accuracy of the evaluation of parameters and characteristics studied.

Keywords: car, perturbation, macro profile, analytical studies, theoretical methods, experiment, approximation, distribution, mileage, speed, projection, motion model.

Background. *The design of cars, the choice of design parameters of units and aggregates is carried out using mathematical (calculating) models [1–3]. Theoretical methods allow performing research of the dynamic properties of an object at early stages of design work. When studying a mathematical model, the significance of the final result depends to a large extent on the way in which the perturbations are formed. The movement of vehicles under operating conditions occurs with random variations in speed due to the longitudinal relief of the road (macro profile), the type of micro profile and the state of the road surface, infrastructure, traffic intensity and other factors, including subjective ones.*

The speed of movement is recognized as a decisive factor that forms the perturbation of the supporting surface. Analytical studies of vibration loading, longevity, fuel efficiency and other operational properties of cars are based on characteristics that establish the relationship between the distance traveled (mileage) and the vehicle's travel time at a certain speed.

The main drawback of the methods of calculating the performance indicators of the car is an idealized idea of distribution of mileages in various transmissions of the gearbox [3]. They do not take into account the state of roads changed in recent years, the type of vehicle, traffic conditions and other factors. In addition, the techniques are based on the assumption of normal laws for the distribution of mileage (time of motion) on each of the gears and the speed of the car, depending on the mileage. In some cases, the distributions are refined by means of empirical coefficients [4].



Pic. 1. Characteristics of the macro profile: 1 – discrete experimental; 2 – distribution density of the normal law.

Reliability of the results of calculations increases with the use of experimentally established distributions of relative mileages or approximating their analytical dependencies, correlated with the type of road macro profile (terrain). The main difference between the obtained experimental data on the distribution of the mileages is the increase in the mileage fraction on the higher–fifth gear and the decrease in the mileage fraction in the third and fourth gears. The explanation of this fact may be due to an increase in the speed of movement of cars outside the city, due to the increase in the specific power of the engine. The results of this kind are confirmed, in particular, by the work closely related to the subjects of the tasks, performed at the Bauman MSTU [5].

In this article we give information about the experimental studies performed by the authors [6–8]:

– macro profile of suburban roads of the central Russia (Nizhny Novgorod region), their systematization is proposed, depending on the type of terrain;

– distributions of time and mileages on each of the gears and for different routes;

– distributions of relative values of mileages time of movement, depending on the speed and the gear used.

Objective. *The objective of the authors is to consider different aspects connected with distribution of characteristics of car movement.*

Methods. *The authors use general scientific and engineering methods, modeling, comparative analysis, mathematical methods.*

Results.

Research of roads' macro profile

The routes chosen within Nizhny Novgorod region were characterized by terrain relief and the presence of a ravine-girder net. Their length was from 50 to 150 km and depended on the longitudinality of the relief. The parameters of the longitudinal angles distributions of the macro profile of the traffic routes are determined by the method of recording geographic coordinates and gradients of the road using the Google Earth application. To assess the statistical reliability of the obtained characteristics, further experimental studies of the macro profile were carried out. It is established that the necessary conditions for the stationarity of the random processes under investigation are fulfilled at a size of selective realizations of 60 km for a strongly crossed terrain and 40 km for a terrain with a small number of gentle hills.

To determine the law of distribution and quantitative characteristics of the distribution density of longitudinal angles (inclinations) of the road, a data processing technique with a conventional geospatial «mileage–height above sea level» was applied [6]. It was noted that the approximation of the experimentally obtained discrete dependence of the distribution curve of the normal law (Pic. 1) cannot be considered successful. The discrepancy between the density distribution of the longitudinal angles of the macro profile is normal due to technological impacts on the surface during the construction of country roads, as a result of which relatively small inclinations of the path are smoothed out, and descents and lifts of considerable length change significantly less. The analytical dependence, which is more in line with the experimentally obtained discrete distribution, consists of two components with normal distribution laws and can be represented by the expression

$$\rho(\alpha_i)=k_1\frac{\Delta\alpha}{\sigma_1\sqrt{2\pi}}e^{-\frac{(\alpha_i)^2}{2\sigma_1^2}}+k_2\frac{\Delta\alpha}{\sigma_2\sqrt{2\pi}}e^{-\frac{(\alpha_i)^2}{2\sigma_2^2}}, \qquad (1)$$

where σ_1, σ_2, k_1, k_2 are distribution parameters, $(k_1+k_2)=1$, $\alpha_{i(j+1)}=\alpha_{ij}+\Delta\alpha$, $\Delta\alpha=0{,}5^o$, $\alpha_i=0{,}5(\alpha_{ij}+\alpha_{i(j+1)})$.

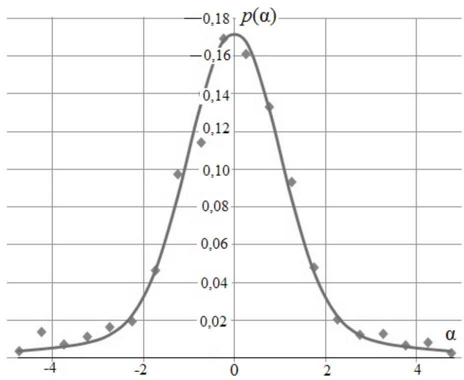
Pic. 2 shows the characteristic of the distribution density of longitudinal angles of the macro profile of the test section, obtained by approximating the discrete experimental dependence by means of the expression (1).

As a result of the research, the systematization of types of road macro-profile according to the degree of «hilliness» is proposed, differing: maximum values of longitudinal angles α_{max}; the maximum values of the probability density $p(0)$ for $\alpha = 0$; the probability density $p(1^\circ)$, $p(2^\circ)$, $p(3^\circ)$, corresponding to the longitudinal angles of the macro profile α equal to 1°, 2°, 3°.

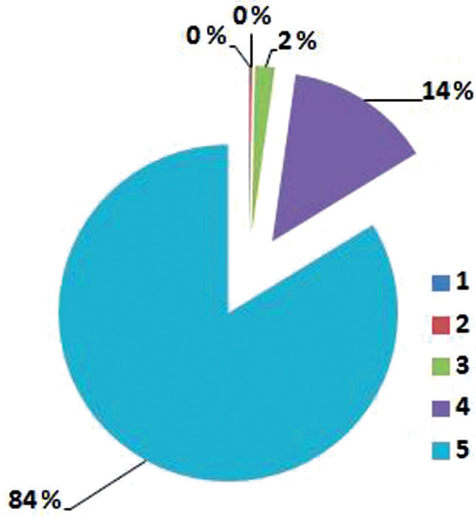
Among the chosen routes of movement with an unambiguous trend of characteristics of the macro profile there are those in which relatively flat and long sections of the path are replaced by long steep ascent and descent. They are classified as a «complex macro profile». The designations of macro profile types in accordance with the values of the probability density of longitudinal angles and the degree of «hilliness» of the road, proposed by the authors, are listed in Table 1 and have conditionality.

Methods of testing and data processing

The object of the study was a light commercial vehicle GAZelle NEXT with a load capacity of 1,5 tons with a diesel engine CUMMINS ISF 2.8 equipped with an electronic control unit. The structure of the unit includes a CAN bus intended for the transmission of control and information commands. The bus signals were processed using the optional Electronic control module (ECM), which provides the registration of: crankshaft speed, instantaneous vehicle speed, travel time, instant fuel consumption and other parameters. The ECM device records signals at a predetermined time interval of 0.8 seconds. The method of recording and processing sensor signals gives an idea of the



Pic. 2. The probability density of longitudinal slopes of the road macro profile.



Pic. 3. Relative mileage on gears.

continuous uneven movement of the car, consisting of individual modes (acceleration, constant speed, deceleration), a set of variations of modes within which the speed was assumed to be constant.

Tests were conducted with the most intensive traffic on the road. In order to exclude the influence of subjective factors on the mode of the car's movement, the drivers periodically changed during the test runs. The sections of routes on which the speed of the car was determined by random factors were not taken into account when registering the parameters. The length of the routes was 350–520 km. The measurements were carried out with the vehicle moving in the forward and backward directions.

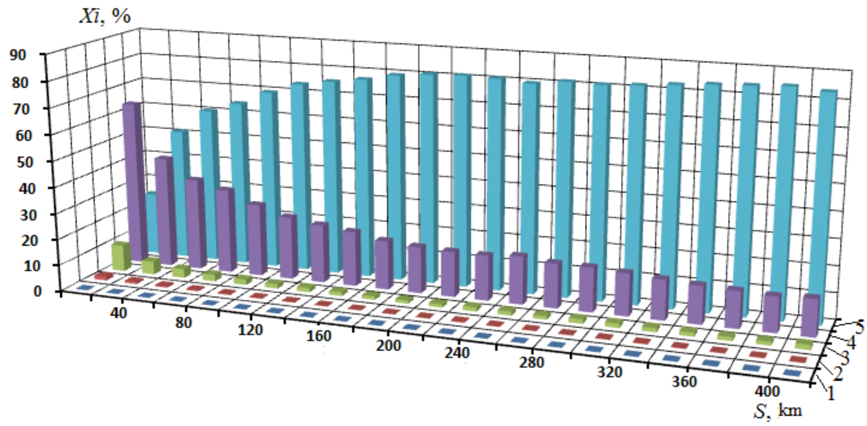
Estimation of statistical characteristics

When calculating the operational performance of the vehicle with analytical methods [4, 5, 8, 9], not only the duration of the movement, but also the

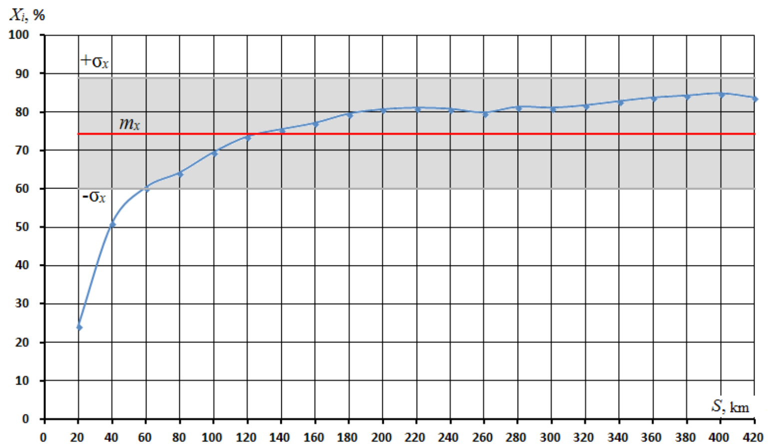
Table 1

Systematization of macro profile types

Name	Designation	α_{max}, °	p(0)	p(1°)	p(2°)	p(3°)
Smooth	P	2,75	0,430	0,290	0,007	–
Average hilly	CX	4,75	0,171	0,011	0,034	0,012
Hilly	X	4,75	0,190	0,089	0,046	0,180
Complex	C	4,75	0,214	0,078	0,039	0,210



Pic. 4. Discrete sets of random values of relative mileages, depending on the sample size and gear.



Pic. 5. Relative mileage, depending on the sample size and gear.

possible changes in speed on each of the gears is important.

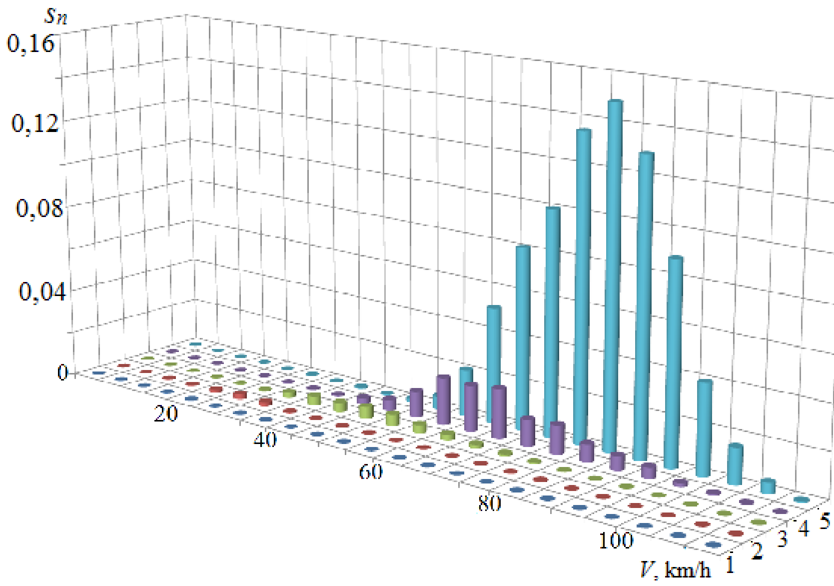
The duration of the movement is measured by time or mileage. Analysis of the vehicle's movement along the test routes is performed using the experimental distributions of random discrete values of the milieage (time) and the speed of movement, depending on the gear. Random characteristics of the mileage (time) can be considered as relative. Relative mileage is the ratio of the total mileage in a given gear to the length of the route. Relative time is the ratio of the total time of movement in a given gear to the time of travel within the route.

To obtain statistically reliable information about the laws of the distribution of the speed of motion, studies of the character of the stationarity of random discrete sets (a variation series) of the values of the relative mileages on each of the gears are performed, depending on the values of the relative milieages. Variational series are obtained as functions of the sizes of sample realizations (sample). Arrays of experimental data, corresponding to stationary samples of random

Table 2

Moment functions and coefficients of variation of the relative mileages on the 4th and 5th gears, depending on the type of macro profile

Type of macro profile of the route	No. gear	Sample size, |x, km	Mean value of relative mileages, m_x	Mean square deviation, σ_x	Variation coefficient, V_x,%
Smooth	4	300	0,167	0,022	13,9
	5		0,783	0,025	3,2
Average hilly	4	340	0,195	0,017	8,5
	5		0,720	0,036	5,0
Hilly	4	260	0,144	0,012	8,5
	5		0,798	0,019	2,4
Complex	4	240	0,171	0,013	1,7
	5		0,789	0,016	9,2



Pic. 6. Speed distribution depending on the gear and relative mileage.

processes of relative mileages, make it possible to obtain full information during processing.

As an example, the procedure for processing experimental data obtained by driving a vehicle along a 420 km route to the corresponding P-type road (Table 1) with good quality road pavement is given as an example. Taking into account the priority determined by the magnitude of the milieages on the 4th and 5th gears (98 % of the length of the route), the stationary conditions of sample realizations of relative mileages are studied (Pic. 3).

To estimate stationarity of a random variable, the coefficient of variation V_x is used as a relative measure of the deviation of mean square values from its arithmetic mean value:

$$V_x = \frac{\sigma_x 100\ \%}{m_x}, \quad (2)$$

where m_x is average value of the random variable, σ_x is standard deviation.

In technical tasks, a random process is considered to be practically stationary at values of the coefficient of variation less than 10 %, and conditionally stationary – at values of the coefficient not exceeding 20 %.

Pic. 4 shows the distribution of the relative mileages X_i when moving on the 5th gear, depending on the sample size s_i and gear. To reduce the complexity of processing the test results, the sample sizes were taken as a multiple of 20 km. The calculation of arithmetic mean and mean-square values of relative milieages, variation coefficients is performed separately for each sample. The most complete sample of 420 km in size (the length of the route) has a relatively large variation in the values of the relative ranges X_i and the small equalization of the discrete series of values due to the initial stage (Pic. 5). The established feature of the distribution testifies to the possible nonstationarity of the process under study. The relative equalization of a discrete series of values of relative mileages occurs when the reference point is shifted by at least 80 km.

From this moment, the values of the coefficient of variation for the samples do not differ significantly, the variability of the variational series should be considered insignificant, and the process is practically stationary.

Results of the calculation of moment functions and coefficients of variation, depending on the type of macro profile and gear in Table 2.

Distributions of motion speed

It is established that the speed of the car is a multiparameter function and depends on the characteristics of the macro profile of the route sections, gear and a number of subjective factors.

In the construction of speed distributions, depending on the gear used and the relative mileage (Pic. 6), arrays of random variables of relative mileages corresponding to the stationarity condition are allocated from the data array and the corresponding arrays of speed data. For each gear, a range of speed changes is set, which is divided into intervals ΔV_i = 5 km/h. In the intervals ΔV_i, the instantaneous (measured) values of the speed V_i, greater or equal to the minimum value of the speed V_{nmin} of the interval «n», and smaller than the maximum speed V_{nmax} of this interval are assigned.

The next step of the data processing algorithm determines the relative mileage values for the ΔV_i intervals in the speed range of each gear.

Within the sampling implementation, the distance traveled during the travel time on each gear is found in accordance with the expression

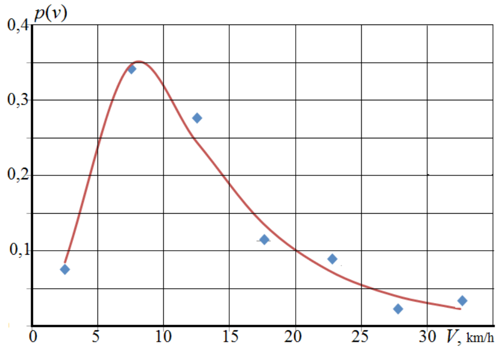
$$s_{\Sigma n} = \sum_{j=1}^{k}\sum_{i=1}^{m} s_i = \sum_{j=1}^{k}\sum_{i=1}^{m} v_i t_{vi}, \quad (3)$$

where $s_{\Sigma n}$ is total mileage on the gear; n – gear number; v_i – speed within the interval ΔV_i; t_{vi} – time of movement at a speed v_i within the interval ΔV_i; s_i – mileage at a speed v_i; k – number of intervals ΔV_i in the range of speed change on the gear n; m – number of measured values of speed within the interval.

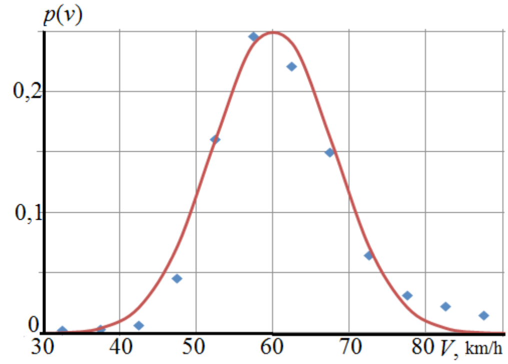
The relative mileage on the gear is determined by the expression

$$s_n = \frac{s_{\Sigma n}}{\sum_{n=1}^{5} s_{\Sigma n}}, \quad (4)$$

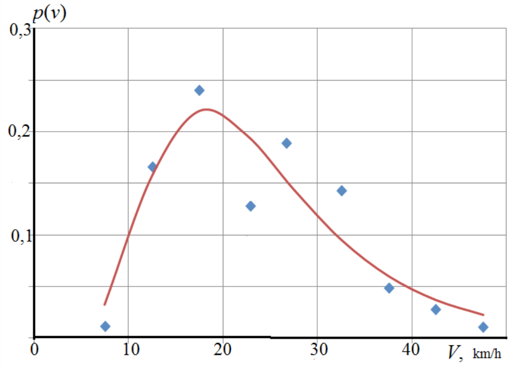
where s_n is relative mileage on the n-th gear.



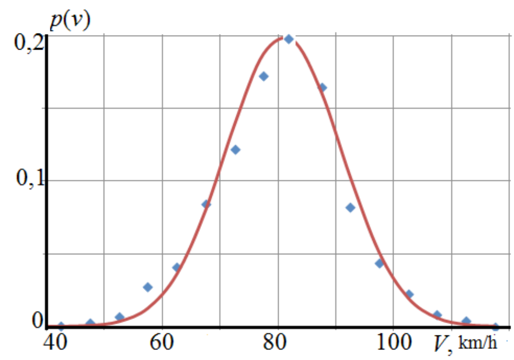
Pic. 7. Curve of speed distribution, gear 1.



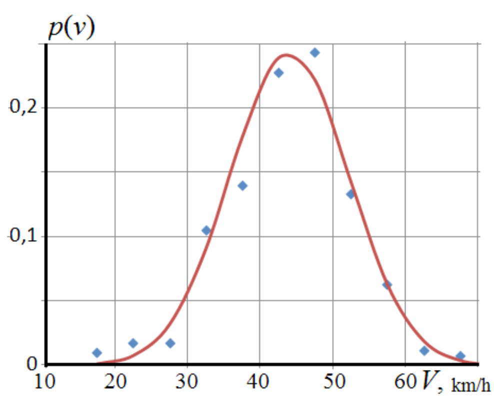
Pic. 10. Curve of speed distribution, gear 4.



Pic. 8. Curve of speed distribution, gear 2.



Pic. 11. Curve of speed distribution, gear 5.



Pic. 9. Curve of speed distribution, gear 3.

Pic. 6 shows the discrete characteristics of the speedy distribution as a function of the relative mileage in each gear.

In Pic. 7–11 discrete speed distributions are represented by separate points, continuous approximations of discrete dependencies are obtained as a result of their processing by the method of least mean squares. Experimental speed distributions can be approximated by analytic expressions. It is established that on roads with any of the types of macro profiles examined, the speed distributions when moving on the 1st and 2nd gears are close to the logarithmically normal law, and on higher gears they correspond to the normal law. The expression for calculating the probability density of the speed of motion in a given interval (time, mileage) for the log-normal distribution law has the form:

$$\rho(V_I)=\frac{\Delta V}{\sigma_{VI}V_I\sqrt{2\pi}}\,e^{-\frac{(\ln V_I-a)^2}{2\sigma_{VI}^2}}, \qquad (5)$$

where a, σ_{VI} – distribution parameters; $V_{I(j+1)}=V_{I(j)}+\Delta V$, $\Delta V=5$ km/h, $V_I=0,5\,(V_{I(j)}+V_{I(j+1)})$, $V_I=\left(\overline{V_I^{\min},\ V_I^{\max}}\right)$ – minimum and maximum values of the range of speed change.

The expression for calculating the probability density of the speed of motion under the normal distribution law:

$$\rho(V_i)=\frac{\Delta V}{\sigma_{Vi}\sqrt{2\pi}}\,e^{-\frac{(V_i-\overline{V_i})^2}{2\sigma_{Vi}^2}}, \qquad (6)$$

where $\overline{V_i}$, σ_{Vi} – distribution parameters; $\Delta V=5$ km/h, $V_{i(j+1)}=V_{i(j)}+\Delta V$, $V_i=0,5(V_{i(j)}+V_{i(j+1)})$, $V_i=\left(\overline{V_i^{\min},\ V_i^{\max}}\right)$, V_i^{mix}, V_i^{max} – minimum and maximum values of the ranges.

The parameters of the speed distribution by mileage, depending on the gear when driving a car category N_1 on roads with a macro profile of types P, CX, X, C are given in Tables 3 and 4.

Conclusion. *The experimental and theoretical vehicle speed distributions and the analytical dependencies approximating them make it possible to simulate the movement of a car for the purpose of an analytical study of the performance indicators for the main types of roads in the central part of the Russian Federation. The obtained data provide a comparative analysis of design variants of units and*

Table 3

Parameters of speed distributions depending on the gear for roads of types P and CX

No. gear	Parameters of speed distribution									
	a		$\overline{V}_i$		σ_{Vi}		V_i^{min}		V_i^{max}	
	P	CX	P	CX	P	CX	P	CX	P	CX
1	2,4	2,3	–	–	0,63	2,3	0	0	50	35
2	3,1	3,4	–	–	0,45	3,4	5	10	50	55
3	–	–	44	48	8,2	11	15	15	85	85
4	–	–	60	61	7,9	9	20	20	105	100
5	–	–	81	79	10	11	25	25	120	100

Table 4

Parameters of speed distributions depending on the gear for roads of types X and C

No. gear	Parameters of speed distribution									
	a		$\overline{V}_i$		σ_{Vi}		V_i^{min}		V_i^{max}	
	X	C	X	C	X	C	X	C	X	C
1	2,9	2,6	–	–	0,63	0,60	0	0	50	50
2	3,4	3,2	–	–	0,20	0,48	5	5	85	75
3	–	–	49	54	12	15,0	20	15	90	85
4	–	–	65	62	12	9,8	25	20	110	100
5	–	–	81	77	11	9,0	30	30	115	105

aggregates, or models of vehicles of one category, or close by the main mass and technical characteristics.

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