Loading modes of the chassis elements of an energy efficient trucks based on road load data

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Abstract. In the process of designing a energy efficient truck, it is especially important to choose representative loading modes to assess the compliance of the undercarriage elements of the chassis with the requirements of strength and durability. The undercarriage elements of the chassis include components and systems that perceive loads and ensure the mobility of the energy efficient truck. The authors of the article focus on the design of the hull parts of the drive axle. The body parts of the drive axle perceive loads from the road and transfer them to the sprung parts. Failure of this power structure means the risk of an emergency, so the power structure must be carefully checked, especially with regard to strength properties and durability. The authors of the article are skeptical about the current requirements and regulations for testing and design studies of driving axles from the point of view of their sufficiency and validity against the background of a comparative analysis of foreign approaches to checking the operational reliability and equipment of testing laboratories. The result of this article is the proposal of a cascade of loading modes for computational modeling of the loading of the undercarriage elements at the initial stages of designing an energy efficient truck. The aim of the work is to develop computational methods for modeling strength and durability in the process of designing an energy efficient truck by developing a reasonable proposal for a cascade of loading modes indicating requirements in the form of a minimum number of cycles before failure and the value of elongation at the sites of failure development.

1 Introduction

Designing the undercarriage elements that meet the operational requirements of strength and durability is an important engineering task. Requirements for the safety and reliability of vehicle components and systems with the progress in the field of mechanical engineering are becoming more stringent and more difficult to achieve against the background of the trend of increasing energy efficiency and competitiveness. This work is devoted to an urgent topic in the direction of improving the efficiency and representativeness of research on the strength and durability of body parts of drive axles as elements of the chassis of vehicles of category

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N (trucks). The process of load research includes an unambiguous solution of the following engineering tasks:

- formation of loading modes;
- formation of requirements for strength and durability;
- determination of loads on the body parts of the drive axle;
- modeling of the stress-strain state of the housing assembly;
- analysis of strength and durability to form a conclusion about the need to refine the geometry of body parts or change the nomenclature of the material.

To solve the tasks set, automated software complexes for multibody system modeling in sequential conjunction with finite element modeling software packages have become the most widespread. However, knowledge of effective tools is not enough: the more important issue is the availability of sound, informative and understandable methodological materials for solving such problems. Therefore, this article is in the nature of a proposal regarding the formation of design loading modes and requirements for strength and durability. It is worth noting that made a special contribution to the direction of regime measurement and determination of vehicle loads such scientists and researchers as N.N. Yatsenko [1,2], S.F. Bezverhiy [3], D.M. Dubinkin [4], I.S. Chichekin and D.S. Vdovin [5], V.N. Lata [6], G.S. Pahwa [7], P. Johannesson and M. Speckert [8], B. Zhang [9] and many other researchers. In terms of research on hull parts of driving axles, the authors of the article note the significant contribution of such scientists and researchers as A.M. Zakharik [10], P.P. Kapusta [11-17], S.M. Minyukovich [18], S.P. Mokhov [19], A.M. Abramov and A.S. Kovalev [20].

The domestic practice of checking the hull parts of the drive axle is based on tests to assess stiffness and strength by applying vertical forces at the installation sites of elastic elements of the springing system. At the same time, it should be noted that there is a tendency to reduce the requirements for the coefficient of static strength of the crankcase housing. The coefficient of static strength reserve is understood as the coefficient K, determined by the formula (1).

$$K = \frac{P_y}{P_n} \qquad (1)$$

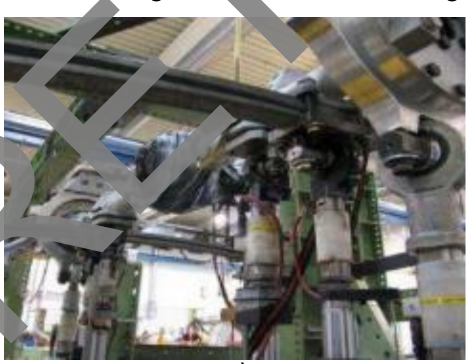
where P_y - the vertical force corresponding to the beginning of plastic deformation (in the design of the crankcase housing, tensile stresses equal to the yield strength of the base material arise under the action of this load), N; P_n - the nominal vertical load on the bridge (static vertical load corresponding to the full load of the vehicle), N.

Thus, comparing the invalid standard OST 37.001.674-2002 [21] and the current standard GOST R 53804-2010 [22], we can note a decrease in the requirements for the coefficient of static strength:

- for vehicles that are operated without restrictions of road conditions (operated mainly off-road), the static strength margin decreased from 5.5 to 4.5;
- for vehicles that are designed to operate mainly on paved roads (operated mainly on public roads), the static strength margin decreased from 4.0 to 2.75;

In connection with the above, the current standards and regulations that form the procedures and requirements for checking the operational reliability of body parts of driving axles of cars cause concern to the authors of the article due to the lack of validity of the accepted criteria, at least with respect to the values of safety factors. The authors of the article do not know both the reasons for the change in these requirements and the source of their appearance. In addition, the current standard [22] does not provide for checking the carrying structure of the drive axle assembly with modes that cause not only vertical loads. The danger of various types of modes that characterize the complex loading of the drive axle assembly (for example, braking or cornering), and their importance for taking into account when checking strength and durability, is noted in the source [10].

It should be understood that the nature of the transfer of loads from unsprung to sprung parts is largely determined by the type of springing system and the quality of the vehicle chassis settings. Changing even one parameter of the springing system (for example, the stiffness of an elastic element or its free length) vehicle significantly affect the accumulation of damage in the undercarriage elements and the level of peak loads under relatively identical and idealized operating conditions and loading modes. For this reason, the classical experimental approach of regime measurement is widespread abroad to confirm design loads, which provides for measuring the actual values of dynamic loads in the contact spot of wheels with the road during the movement of an analog or prototype vehicle under development in the modes of daily and formal operation. [8] The control measurement approach has proven its technical effectiveness, since it determines the values of maximum standard loads based on field tests and allows you to design chassis elements based on reasonable load values. It is also worth noting the fact that laboratory tests to verify strength and durability abroad provide for multicomponent loading of the drive axle assembly with a springing system, since not always dangerous hubs arise only from the action of vertical loads, which is confirmed by sources [10,23]. As examples of the process of full-scale tests on complex multicomponent test benches to check the strength and durability of body parts of the drive axle assembly with a springing system, the illustrations in Figure 1 are presented. Among the available information sources, there is no mention that similar multicomponent testing equipment is available or used in domestic laboratories – this omission is due at least to a low level of technical justification for the use of similar equipment, as well as a lack of understanding of the need for this equipment due to insufficient knowledge of how the drive axle assembly works and loads in during operation. The last century in the development of domestic testing equipment was characterized by a tendency to simplify test methods, while abroad the trend was observed in the direction of rational technical complication of equipment in order to bring laboratory tests as close as possible to accelerated full-fledged simulation of the work of the research object. Therefore, the issue of technical perfection of the products being developed and the need to maintain a level of competition at least in terms of compliance of the chassis elements with the requirements of strength and durability is relevant, and is closely related to the direction of development of the technical level of domestic testing laboratories and measuring equipment.



ÇaÈ

ÇbÈ

ÇcÈ

Fig. 1. Test benches for testing the strength and durability of the drive axles assembled: ÇaÈ - a test bench with an imitation of 10 force components for the left and right sides (two longitudinal Fx forces, two lateral forces Fy, force Fzo from the bump, vertical force Fzu from the elastic elements, two braking moments Mut); ÇbÈ - a test bench with simulation of 8 force components for the left and right sides (two longitudinal forces Fx, two lateral forces Fy, two vertical forces Fz from the elastic elements, two braking moments Mut); ÇcÈ - a test bench with an imitation of 5 force components (two longitudinal forces Fx, one lateral force Fy, two vertical forces Fz). [24]

The authors of the article are interested in developing reasonable and effective ways to check the hull parts of drive axles, as the undercarriage elements of the chassis, at the design stage, since a comparative analysis of domestic and foreign approaches suggests that domestic verification methods require further development both at the design stage of components and at the testing stage. The level of compliance of the final product with the consumer properties of strength and durability depends on the qualitative study of verification methods. That is why the work is aimed at solving topical issues of the technical validity of the accepted loading modes and requirements for strength and durability in relation to checking the undercarriage elements of the chassis of vehicle of a category N (truck).

2 Providing the road tests (road load data acquisition)

The evidence base for the need to develop domestic methods of designing and testing the undercarriage elements of the chassis is based on road load data acquisition. In 2023, part of a large research work on the alignment of category N vehicles (trucks) was carried out at the proving ground of PJSC ÇKAMAZÈ, with the cooperation of the PJSC ÇKAMAZÈ, and the Bauman Moscow State Technical University. Mode measurement involves recording wheel loads and vehicle movement parameters in various operating conditions and modes. At the moment, only part of the work has been carried out, taking into account the implementation of modes of simulation of the conditions of daily operation on the roads of the proving ground of PJSC ÇKAMAZÈ, which is demonstrated in this work.
The general view of the research object is shown in Figure 2.

Fig. 2. General view of the object of study (KAMAZ 63934)

The parameters of the object of study are presented in Table 1. The given information on weight was obtained by measuring on a weighing test bench for the object of study, fully prepared for testing - the measuring equipment, the test driver, process fluids and ballast are taken into account.

Table 1. Parameters of the object of study (KAMAZ 63934)

Parameter	**Description**
Factory brand	KAMAZ
Modification	63934
Wheel formula	4 x 2
Engine: - manufacturer - model - factory number	 Cummins ISB6.7E5310 86109730
Gear box: - type - number of gears - front drive rations	 automated 9 9,48; 6,58; 4,68; 3,48; 2,62; 1,89; 1,35; 1,00; 0,75
Main gear ratio	4,625
Tires: - front axle - rear axle	 KAMA NF702 13R22.5 156/150K KAMA NR702 13R22.5 156/151K
Mass of measure vehicle: - overall mass - front axle left wheel right wheel - rear axle left wheel right wheel	 8255 kg 5155 kg 2645 kg 2510 kg 3100 kg 1575 kg 1525 kg

Table 2. List of measuring parameters

№	Channel name	Unit	Error	Frequency rate	Range
1	Longitudinal force in the wheel center of the front left wheel FA_le_Fx	[kN]	±2 [%]	100 [Hz]	±180 [kN]
2	Longitudinal force in the wheel center of the front right wheel FA_ri_Fx	[kN]	±2 [%]	100 [Hz]	±180 [kN]
3	Longitudinal force in the wheel center of the rear left wheel RA_le_Fx	[kN]	±2 [%]	100 [Hz]	±180 [kN]
4	Longitudinal force in the wheel center of the rear right wheel RA_ri_Fx	[kN]	±2 [%]	100 [Hz]	±180 [kN]
5	Lateral force in the wheel center of the front left wheel FA_le_Fy	[kN]	±2 [%]	100 [Hz]	±100 [kN]
6	Lateral force in the wheel center of the front right wheel FA_ri_Fy	[kN]	±2 [%]	100 [Hz]	±100 [kN]
7	Lateral force in the wheel center of the rear left wheel RA_le_Fy	[kN]	±2 [%]	100 [Hz]	±100 [kN]
8	Lateral force in the wheel center of the rear right wheel RA_ri_Fy	[kN]	±2 [%]	100 [Hz]	±100 [kN]
9	Vertical force in the wheel center of the front left wheel FA_le_Fz	[kN]	±2 [%]	100 [Hz]	±180 [kN]
10	Vertical force in the wheel center of the front right wheel FA_ri_Fz	[kN]	±2 [%]	100 [Hz]	±180 [kN]
11	Vertical force in the wheel center of the rear left wheel RA_le_Fz	[kN]	±2 [%]	100 [Hz]	±180 [kN]
12	Vertical force in the wheel center of the rear right wheel RA_ri_Fz	[kN]	±2 [%]	100 [Hz]	±180 [kN]
13	Torque around X axis in the wheel center of the front left wheel FA_le_Mx	[kNm]	±2 [%]	100 [Hz]	±30 [kNm]
14	Torque around X axis in the wheel center of the front right wheel FA_ri_Mx	[kNm]	±2 [%]	100 [Hz]	±30 [kNm]
15	Torque around X axis in the wheel center of the rear left wheel RA_le_Mx	[kNm]	±2 [%]	100 [Hz]	±30 [kNm]
16	Torque around X axis in the wheel center of the rear right wheel RA_ri_Mx	[kNm]	±2 [%]	100 [Hz]	±30 [kNm]
17	Torque around Y axis in the wheel center of the front left wheel FA_le_My	[kNm]	±2 [%]	100 [Hz]	±30 [kNm]
18	Torque around Y axis in the wheel center of the front right wheel FA_ri_My	[kNm]	±2 [%]	100 [Hz]	±30 [kNm]
19	Torque around Y axis in the wheel center of the rear left wheel RA_le_My	[kNm]	±2 [%]	100 [Hz]	±30 [kNm]
20	Torque around Y axis in the wheel center of the rear right wheel RA_ri_My	[kNm]	±2 [%]	100 [Hz]	±30 [kNm]
21	Torque around Z axis in the wheel center of the front left wheel FA_le_Mz	[kNm]	±2 [%]	100 [Hz]	±30 [kNm]

№	Channel name	Unit	Error	Frequency rate	Range
22	Torque around Z axis in the wheel center of the front right wheel FA_ri_Mz	[kNm]	±2 [%]	100 [Hz]	±30 [kNm]
23	Torque around Z axis in the wheel center of the rear left wheel RA_le_Mz	[kNm]	±2 [%]	100 [Hz]	±30 [kNm]
24	Torque around Z axis in the wheel center of the rear right wheel RA_ri_Mz	[kNm]	±2 [%]	100 [Hz]	±30 [kNm]
25	X vehicle coordinate	[m]	±0.5 [%]	5 [Hz]	-
26	Y vehicle coordinate	[m]	±0.5 [%]	5 [Hz]	-
27	Z vehicle coordinate	[m]	±0.5 [%]	5 [Hz]	-
28	Vehicle speed	[km/h]	±0.5 [%]	5 [Hz]	till 50 [km/h]
29	Angle speed of the front left wheel	[rpm]	±2 [%]	100 [Hz]	till 3000 [rpm]
30	Angle speed of the front right wheel	[rpm]	±2 [%]	100 [Hz]	till 3000 [rpm]
31	Angle speed of the rear left wheel	[rpm]	±2 [%]	100 [Hz]	till 3000 [rpm]
32	Angle speed of the rear right wheel	[rpm]	±2 [%]	100 [Hz]	till 3000 [rpm]
33	Steering wheel angle	[¡]	±0.5 [%]	100 [Hz]	till 700 [¡]
34	Number of gear	[-]	-	10 [Hz]	-
35	Engine torque	[kNm]	-	100 [Hz]	-
36	Angle speed of engine	[rpm]	-	100 [Hz]	-
37	Acceleration pedal position	[%]	-	10 [Hz]	-
38	Brake pedal position	[%]	-	20 [Hz]	-

Kistler Road Dance 6 HT System 2000 measuring wheels were used to measure wheel loads (positions 1-24 from Table 2). Figure 3 shows photos of the installation of measuring equipment at the test site.

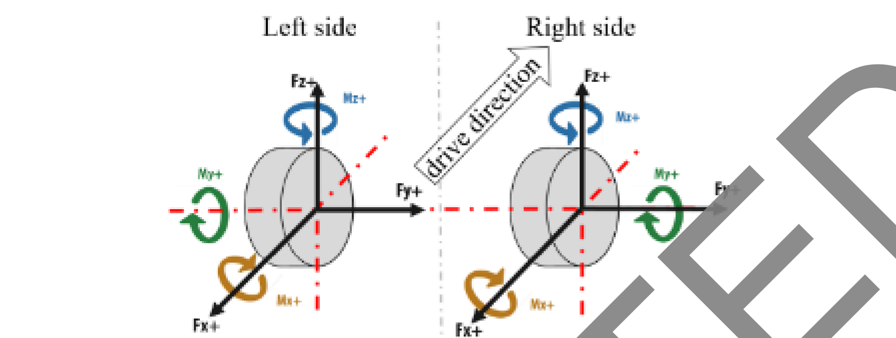
Fig. 3. Installation of measuring equipment on KAMAZ 63934

As part of the test preparation procedure, the coordinate system of the measuring wheels and the operability of the external telemetry were checked in accordance with the program shown in Table 3. Table 3 shows the correspondence of the signs of the directions of forces and moments to the coordinate system of the measuring wheels acting on the hub during the movement of the car during each of the test maneuvers. If the signs of the direction of forces did not match and inadequate load values were obtained, troubleshooting measures were taken in accordance with the documentation for the Kistler RoadDyn S6HT System 2000 measuring wheels [24].

Table 3. Signs of the direction of forces and torques

Test program	Signs of forces and moments in accordance with the coordinate system (see the picture below the table) ÇFLÈ – front left; ÇFRÈ – front right; ÇRLÈ – rear left; ÇRRÈ – rear right																							
	Fx, [kN]				Fy, [kN]				Fz, [kN]				Mx, [kNm]				My, [kNm]				Mz, [kNm]			
Wheel	FL	FR	RL	RR	FL	FR	RL	RR	FL	FR	RL	RR	FL	FR	RL	RR	FL	FR	RL	RR	FL	FR	RL	RR
Static									+	+	+	+												
Acceleration	-	-	-	-													+	+	+	+				
Braking	+	+	+	+													-	-	-	-				

Left turn					-	-	-	-					-	-	-	-					-	-	-	-
Right turn					+	+	+	+					+	+	+	+					+	+	+	+



The configurations and calibration information for each measuring wheel are shown in Figure 4.

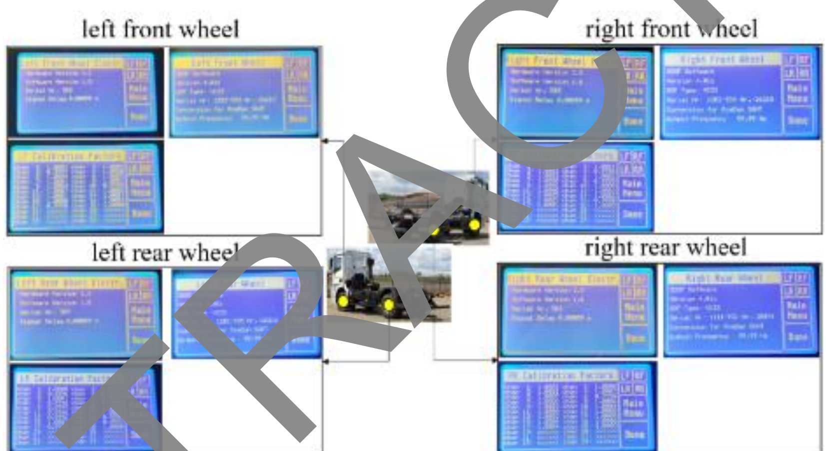


Fig. 4. Configuration of wheel hub transducers RoadDyn S6HT System 2000

The test program was formed on the basis of the technical equipment of the NTC testing ground of PJSC ÇKAMAZÈ, taking into account compliance with the requirements of safe operation and taking into account the compliance of recorded loads with the modes of daily operation. The developed test program is presented in Table 4. As part of the implementation of the test program and the additional elimination of registration errors, each mode was repeated three times during the testing process.

Table 4. The program to imitate the conditions of daily operation on the public roads of the proving ground of the PJSC ÇKAMAZÈ

№	Mode name	Maximum speed
1	Acceleration and braking when moving forward and rearward (4 types of test on dry asphalt pavement – acceleration and braking levels <0.5g).	60±2 km/h
2	Overcoming climbs of 6-18% in front (3 types of test on slopes of 6%, 12% and 18% on dry asphalt pavement – smooth acceleration from a place without slipping of the driving wheels).	15±2 km/h

№	Mode name	Maximum speed
3	Overcoming climbs of 6-12% in reverse (3 types of test on slopes of 6%, 12% and 18% on dry asphalt pavement – smooth acceleration from a place without slipping of the driving wheels).	10±2 km/h
4	Stop when driving in front at 6-18% ascents (3 types of test on slopes of 6%, 12% and 18% on dry asphalt pavement – movement on the rise followed by a stop at the end of the climb).	10±2 km/h
5	Stopping when reversing on ascents of 6-12% (2 types of test on slopes of 6% and 12% on dry asphalt pavement – movement on the rise followed by a stop at the end of the climb).	10±2 km/h
6	Straight–line movement while maintaining of constant speed (3 types of test on dry asphalt pavement - moderate acceleration with acceleration ≤0.3g, followed by maintaining a constant speed).	30±2 km/h
7	Driving at minimum speeds (1 type of test on a dry asphalt surface).	5±2 km/h
8	Rolling motion (1 type of test on a dry asphalt concrete surface).	40±2 km/h
9	Parking maneuvering (5 types of tests on dry asphalt pavement – steering wheel turns from stop to stop in place, including with the brake pedal clamped and at low speeds).	15±2 km/h
10	Driving in turn (2 types of test on a dry asphalt pavement – movement at speeds until of 20 and 40 km/h with lateral accelerations ≤ 0.5g).	40±2 km/h
11	The "lane change" maneuver according to the marking (2 types of test on a dry asphalt pavement – movement at speeds of 20 and 40 km/h with lateral accelerations ≤ 0.5g).	40±2 km/h
12	The "double lane change" maneuver according to the marking (2 types of test on dry asphalt pavement – movement at speeds of 20 and 40 km/h with lateral accelerations ≤ 0.5g).	40±2 km/h
13	The "snake" maneuver (slalom) according to the marking (2 types of test on a dry asphalt pavement – movement at speeds of 20 and 30 km/h with lateral accelerations ≤ 0.5g).	30±2 km/h
14	The "eight" maneuver according to the marking (2 types of test on dry asphalt pavement – movement at speeds of 20 and 30 km/h with lateral accelerations ≤ 0.5g).	30±2 km/h
15	Steering wheel jerk maneuver (2 types of test on dry asphalt pavement – movement at speeds of 20 and 40 km/h with lateral accelerations of < 0.5g).	40±2 km/h
16	Constant radius cornering 50 m (1 type of test on a dry asphalt pavement – smooth acceleration to a speed of 50 km/h, lateral acceleration level < 0.5g)	50±2 km/h
17	Spiral movement (4 types of test on a dry asphalt pavement – movement to the right and left with steering wheel angles 180¡ and 270°, lateral acceleration level ≤0.5g).	30±2 km/h
18	Driving on a special cobblestone road (3 types of test on a special cobblestone road – steady movement at speeds of 10, 20 and 30 km/h).	30±2 km/h

3 Analysis of test results

The primary analysis of the results was carried out by the method of graphical creating of the following dependencies for each mode:

- the forces and moments of each wheel versus time;
- speed versus time;
- the degree of pressing on the accelerator pedal versus time;
- coordinates of the vehicle in the plane of the road (X & Y coordinates) versus time.

The creating of these graphs made it possible to evaluate each mode for errors and the adequacy of the results. A general example of illustrating the test results for the ÇConstant radius cornering 50 mÈ mode (mode 16 from Table 4) on an asphalt pavement is shown in Figure 5.

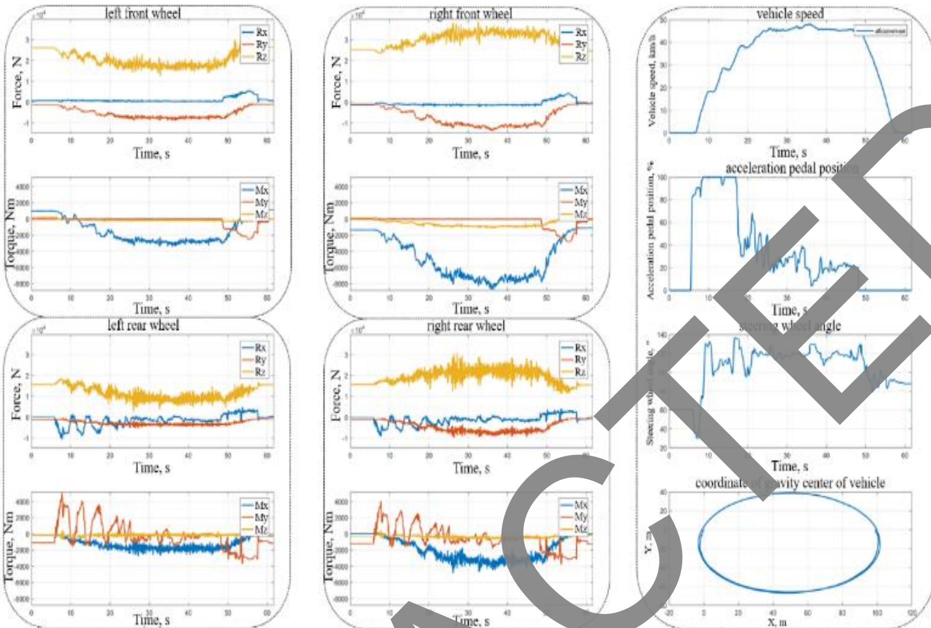


Fig. 5. An illustration of the test results using the example of the ÇConstant radius cornering 50 mÈ mode: Rx – longitudinal forces in the wheel center; Ry – lateral forces in the wheel center; Rz – vertical forces in the wheel center; Mx and Mz – bending torques in the wheel center; My – braking or traction torques around the wheel center (around Y axis).

In order to confirm or refute the data of the current standard [22] with respect to the values of the safety margin coefficients, a preliminary assessment of the maximum effective dynamic loads in the directions of the X, Y and Z axes was carried out by calculating the maximum dynamic load coefficients determined by the general formula (2) from the source [25].

$$K_{d\_j\_i} = \frac{F_{d\_j\_i}}{F_{s\_j\_z}} \tag{2}$$

where $K_{d\_j\_i}$ – the coefficient of maximum dynamic load on the wheel ÇjÈ in the direction of the axis ÇiÈ, [-]; $F_{d\_j\_i}$ – the maximum value of the dynamic load over the time history of the mode on the ÇjÈ wheel in the direction of the ÇiÈ axis, [kN]; $F_{s\_j\_z}$ – the values of the static vertical load on the wheel "j" in the direction of the Z axis, [kN].

The results of determining the average coefficients of maximum dynamic load for the front suspension are presented in Table 5 for each mode, and for the rear suspension in table 6, respectively. Averaging involves determining the average value of three repetitions of registration of the same type of test, as well as the same test group.

Table 5. Calculation of the coefficients of maximum dynamic loads for the front suspension

№	Name mode	Front suspension					
		$K_{d\_FA\_Fx}$		$K_{d\_FA\_Fy}$		$K_{d\_FA\_Fz}$	
	ÇLÈ - left side; ÇRÈ - right side	ÇLÈ	ÇRÈ	ÇLÈ	ÇRÈ	ÇLÈ	ÇRÈ
1	Acceleration and deceleration when moving forward and backward	1.16	1.22	0.04	0.04	1.43	1.46
2	Overcoming climbs of 6-18% in front	0.15	0.16	0.04	0.04	1.16	1.20
3	Overcoming climbs of 6-12% in reverse	0.19	0.20	0.04	0.04	1.19	1.18
4	Stopping when driving in front on ascents 6-18%	0.13	0.14	0.04	0.04	1.16	1.14
5	Stopping when reversing on ascents 6-12%	0.12	0.16	0.04	0.04	1.19	1.18
6	Straight-line movement with the maintenance of constant speed	0.17	0.18	0.04	0.04	1.10	1.06
7	Driving at minimum speed	0.17	0.18	0.04	0.04	1.04	1.06
8	Rolling motion	0.02	0.02	0.04	0.04	1.08	1.08
9	Parking maneuvering	0.31	0.32	0.33	0.35	1.00	1.02
10	Driving in turn	0.08	0.09	0.15	0.12	1.16	1.14
11	The "lane change" maneuver according to the marking	0.08	0.14	0.23	0.26	1.23	1.34
12	The Çdouble lane changeÈ maneuver according to the marking	0.12	0.12	0.29	0.30	1.29	1.30
13	The ÇsnakeÈ maneuver (slalom) according to the marking	0.12	0.12	0.12	0.12	1.18	1.14
14	The ÇeightÈ maneuver according to the marking	0.12	0.12	0.39	0.45	1.27	1.30
15	Steering wheel jerk maneuver	0.17	0.20	0.35	0.18	1.27	1.22
16	Constant radius cornering 50 m	0.13	0.14	0.35	0.49	1.16	1.38
17	Spiral movement	0.19	0.10	0.39	0.57	1.08	1.54
18	Driving on a special cobblestone road	0.12	0.14	0.04	0.06	1.31	1.30

Table 6. Calculation of the coefficients of maximum dynamic loads for the rear suspension

№	Name mode	Rear suspension					
		$K_{d\_RA\_Fx}$		$K_{d\_RA\_Fy}$		$K_{d\_RA\_Fz}$	
	ÇLÈ - left side; ÇRÈ - right side	ÇLÈ	ÇRÈ	ÇLÈ	ÇRÈ	ÇLÈ	ÇRÈ
1	Acceleration and deceleration when moving forward and backward	0.65	0.67	0.06	0.07	1.62	1.60
2	Overcoming climbs of 6-18% in front	0.78	0.80	0.06	0.07	1.49	1.50
3	Overcoming climbs of 6-12% in reverse	0.39	0.33	0.06	0.07	1.49	1.50
4	Stopping when driving in front on ascents 6-18%	0.39	0.40	0.06	0.07	1.46	1.34
5	Stopping when reversing on ascents 6-12%	0.32	0.30	0.06	0.07	1.16	1.40
6	Straight-line movement with the maintenance of constant speed	0.29	0.30	0.06	0.07	1.10	1.07
7	Driving at minimum speed	0.31	0.17	0.06	0.07	1.07	1.07
8	Rolling motion	0.65	0.67	0.06	0.07	1.36	1.54

№	Name mode	Rear suspension					
		$K_{d\_RA\_Fx}$		$K_{d\_RA\_Fy}$		$K_{d\_RA\_Fz}$	
	ÇLÈ - left side; ÇRÈ - right side	ÇLÈ	ÇRÈ	ÇLÈ	ÇRÈ	ÇLÈ	ÇRÈ
9	Parking maneuvering	0.23	0.23	0.06	0.07	0.97	1.02
10	Driving in turn	0.65	0.60	0.16	0.20	1.29	1.20
11	The "lane change" maneuver according to the marking	0.63	0.66	0.52	0.47	1.75	1.54
12	The Çdouble lane changeÈ maneuver according to the marking	0.68	0.60	0.19	0.20	1.65	1.57
13	The ÇsnakeÈ maneuver (slalom) according to the marking	0.58	0.60	0.06	0.07	1.23	1.20
14	The ÇeightÈ maneuver according to the marking	0.65	0.53	0.29	0.33	1.42	2.31
15	Steering wheel jerk maneuver	0.65	0.74	0.19	0.13	1.49	1.34
16	Constant radius cornering 50 m	0.68	0.67	0.13	0.60	1.20	2.04
17	Spiral movement	0.71	0.67	0.16	0.74	1.23	2.01
18	Driving on a special cobblestone road	0.23	0.33	0.10	0.10	1.75	1.94

A summary analysis of the results for the front and rear suspensions shows the following data of the maximum dynamic load limit coefficients for the entire completed test program:

1. In the X-axis direction of the vehicle:
   - minimum value: **0.02**;
   - maximum value: **1.22**.
2. In the direction of the Y axis of the vehicle:
   - minimum value: **0.04**;
   - maximum value: **0.74.**
3. In the direction of the Z axis of the vehicle:
   - minimum value: **1.00** (static vertical load compliance);
   - maximum value: **2.31**.

To understand the level of the obtained dynamic loads, recommended limiting coefficients of equivalent dynamic loads are given for comparison from sources [25,27-29] (the coefficients are valid for vehicles that are operated mainly on public roads):

1. In the X-axis direction:
   - strength testing modes: **<3.00**;
   - multi-cycle fatigue life modes: **<1.50**.
2. In the Y-axis direction:
   - strength testing modes: **<2.00**;
   - multi-cycle fatigue life modes: **<0.80**.
3. In the direction of the Z axis:
   - strength testing modes: **<4.00**;
   - multi-cycle fatigue life modes: **<2.50**.

Thus, a comparative analysis of the obtained and literary coefficients of maximum dynamic loads allows us to conclude that the recorded modes from table 4 correspond to daily operation. This means that in these modes, tensile stresses occur in the undercarriage elements of the chassis belonging to the zone of multi-cycle fatigue life of the base material.

To assess the value of the coefficient of static strength reserve, we apply the ideology of assessing the load on the accumulation of pseudo-damage in terms of borrowing criteria for making of a pseudo-fatigue curve. [8,25-29] The criteria for making of a pseudo-fatigue curve are based on the peculiarities of dividing loading modes into groups of levels of emerging loads at the design stage of the vehicle. When designing the undercarriage elements of the chassis, the durability requirements for multi-cycle fatigue life modes are normalized by the load level in the range $>1 \cdot 10^5$ of the number of Çstatic-mode-staticÈ cycles. It should also be noted that on the basis of the standard [30] the number of cycles $1 \cdot 10^4$ is the boundary of the high-cycle and low-cycle fatigue, and level of activity in the range of $1 \cdot 10^3$ to $1 \cdot 10^5$ number of cycles refers to the forced modes. Forced modes characterize the level of loads that can be used for laboratory tests of individual components and systems of the vehicle in order to further reduce the test time compared to landfills, since they allow accelerated accumulation of necessary damage in the structure while maintaining a stress level not exceeding the yield strength of the base material. The pseudo-fatigue curve is based on the vertical force (since it is the largest in comparison with longitudinal and lateral forces), and the desired dynamic load at number of $1 \cdot 10^3$ cycles on the pseudo-fatigue curve corresponds to the amplitude of the vertical load, at which tensile stresses of the yield strength of the base material in the undercarriage elements of chassis presumably occur. Figure 6 shows an illustration explaining the characteristic points of the pseudo-fatigue curve and the ideology of interpreting the load conditions of one or another group of forcing modes to study individual groups of parts in a vehicle based on the principle of accumulation of pseudo-damage.

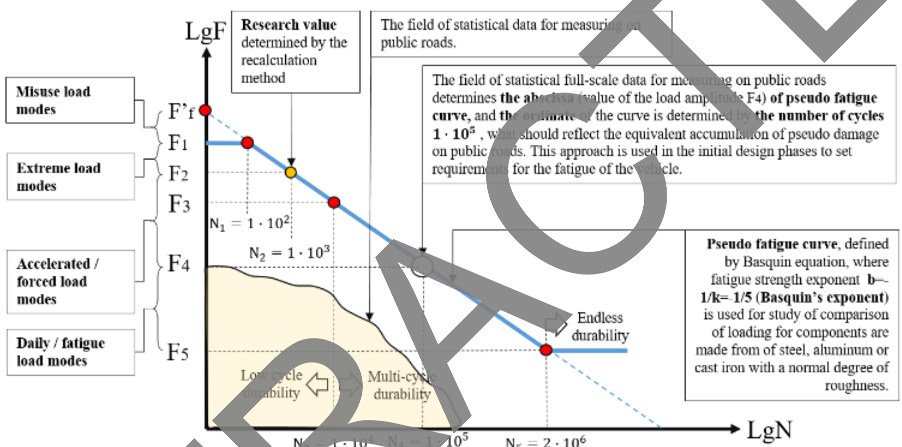


Fig. 6. The ideology of interpretation of modes and quantities for the formation of requirements for the durability of vehicle chassis systems based on sources [8,26].

The simplest pseudo-fatigue curve in accordance with the method [8,27] is described in this case by the Basquin equation according to the formula (3).

$$F_a = F'_f \cdot (2N_f)^b \tag{3}$$

where F_a – the amplitude of the force, [N]; N_f – number of cycles before failure, [-]; F'_f – a constant that determines the point of destruction by the force, [kN]; b - fatigue strength exponent (Basquin's exponent, determines the angle of inclination of the fatigue curve).

The authors of the article propose the creation of a pseudo-fatigue curve based on the recorded road load asquisition data. Since it was previously noted that the recorded modes in accordance with Table 4 relate to the modes of daily operation, their affiliation corresponds to the range of load amplitudes at the level $\leq F_4$. Thus, the abscissa (load amplitude F_4) of the pseudo-fatigue curve is determined by the maximum load amplitude from the recorded road load asquisition data, and the ordinate of the curve is determined by the number of cycles $N_4 = 1 \cdot 10^5$. The exponent ÇbÈ from equation (3) must correspond to the value -1/5, which is the case for the analysis of chassis elements made of steel, aluminum or cast iron.

By the method of schematization (the ÇrainflowÈ method [30]), it was determined that the amplitude of the maximum vertical dynamic load according to the results of field tests corresponds to the value of 14100 [N] with the ordinate assigned to it $N_4 = 1 \cdot 10^5$. The results of the designed pseudo-fatigue curve are shown in Figure 7.

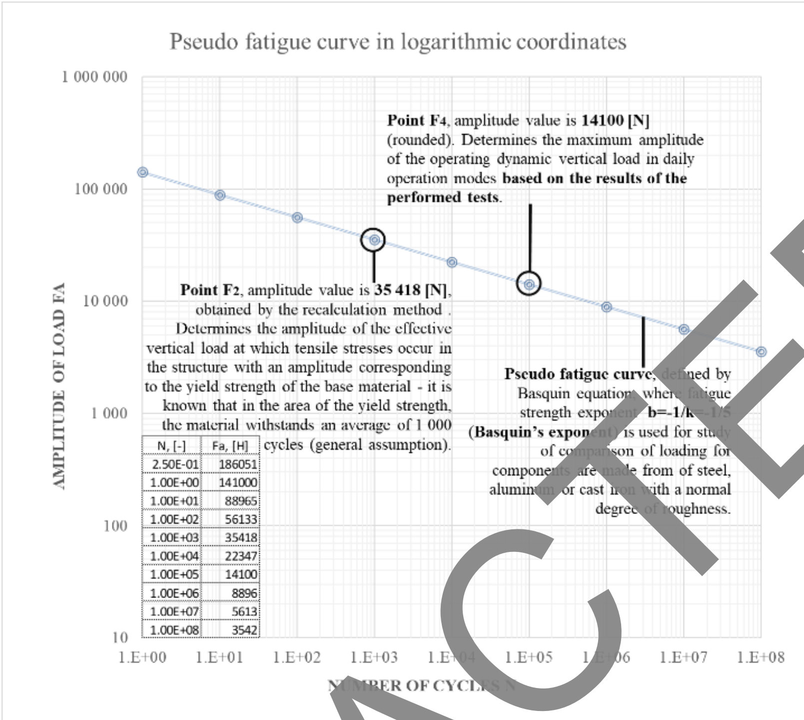


Fig. 7. The pseudo-fatigue curve, reproduced from the test results, for the object of study.

For the designed pseudo-fatigue curve, the point of the assumed yield strength is determined - the magnitude of the amplitude of the vertical load $F_2 = 35\,418$ [N], which is $1 \cdot 10^3$ cycles. To move from the amplitude of the load to the peak value of the dynamic load, it is necessary to make the assumption that the average value of the amplitude corresponds to the static load on the axis where the peak amplitude of the vertical load occurred, namely, the rear right wheel. The static load on the rear right wheel is $F_{z\_RA\_ri} = 14960$ [N] (rounded). Thus, the dynamic vertical load $F_{p\_0.2\%}$, at which yield stress may occur, is defined as the sum of the amplitude and the average value, namely $F_2 + F_{z\_RA\_ri} = 50\,378$ [N].

Using expression (4), assume the coefficient of static strength reserve and compare it with the data of the current standards regarding the requirements for vehicles that are intended for operation mainly on paved roads (operation on public roads).

$$K = \frac{F_{p\_0.2\%}}{F_{z\_RA\_ri}} = 3.37 \text{ (should be } \mathbf{< 2.75} \text{ по GOST R } 53804 - 2010) \tag{4}$$

The results of the study showed that the requirements of the current standard [22] are insufficient and are recommended for revision, moreover, the requirements of the previously existing industry standard [21] are more preferable in this regard (**3.37** < **4.0** according [21] – the condition is fulfilled). Based on the conducted research, the authors of the article recommend revising the coefficient of static strength reserve in the standard [22] in relation to vehicles that are intended for operation mainly on paved roads (operation on public roads), from a value of **2.75** to **3.50** (conservatively rounded).

4 The proposal of design modes for load modeling

Based on the conducted field studies and the already existing experience in the formation of load modes [31] for simulation strength & durability load cases, a proposal has been developed for a list of calculated loading cases of category N vehicles (trucks) at the initial stages of design – see Table 7. Taking into account source [10], the proposal takes into account a cascade of modes that can be applied to assess the operational reliability of chassis elements.

Table 7. Calculation modes recommended for category N vehicles (trucks)

Load case	**G factor** (ÇAÈ) / **Impact factor** (ÇDÈ)			**Requirements for strength & durability** N – number of half cycles Çstatic-load caseÈ, δ – relative plastic strain.
	X longitudinal	**Y** lateral	**Z** vertical	
1 – Static	-	-	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
2 – Forward acceleration	**-0.5*** A	-	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
3 – Rearward acceleration	**0.5*** A	-	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
4 – Forward braking	**0.8*** A	-	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
5 – Rearward braking	**-0.8*** A	-	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
6 – Right turn	-	**0.6*** A	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
7 – Left turn	-	**-0.6*** A	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
8 – Acceleration right turn	**-0.35*** A	**0.35*** A	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
9 – Acceleration left turn	**-0.35*** A	**-0.35*** A	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
10 – Braking in right turn	**0.35*** A	**0.35*** A	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
11 – Braking in left turn	**0.35*** A	**-0.35*** A	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
12 – Diagonal mode (right front & left rear are pasted)	-	-	**2.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
13 – Diagonal mode (left front & right rear are pasted)	-	-	**2.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
14 – Pothole braking (pothole for left wheel)	**0.8*** D	-	**3.0** D	$N > 2 \cdot 10^2$; $\delta \leq 2\%$
15 – Pothole braking (pothole for right wheel)	**0.8*** D	-	**3.0** D	$N > 2 \cdot 10^2$; $\delta \leq 2\%$
16 – Forward shock	**3.0*** D	-	**3.0** D	$N > 2 \cdot 10^2$; $\delta \leq 2\%$
17 – Rearward shock	**3.0*** D	-	**3.0** D	$N > 2 \cdot 10^2$; $\delta \leq 2\%$
18 – Max rebound	-	-	**8.0**** A	$N > 2 \cdot 10^3$; $\delta \leq 0.2\%$
19 – Max bump	-	-	**3.5** D	$N > 2 \cdot 10^3$; $\delta \leq 0.2\%$
20 – Max bump & braking	**2.5*** D	-	**2.5** D	$N > 2 \cdot 10^3$; $\delta \leq 0.2\%$
21 – Forward acceleration on the rise of 10%	**-0.35*** A	-	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
22 – Rearward acceleration on the rise of 10%	**0.35*** A	-	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
23 – Driving along the slope (slope to the right)	-	-	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$
24 – Driving along the slope (slope to the left)	-	-	**1.0** A	$N > 2 \cdot 10^5$; $\delta = 0\%$

Notes:

- all load cases involve checking the vehicle in a total loaded condition;
- ÇAÈ: acceleration coefficient (determines the value of the inertia forces of the vehicle);
- ÇDÈ: the coefficient of maximum dynamic load (determines the value of the dynamic load for the mode as a multiplier to the static vertical load);
- *: the coefficient value can be adjusted taking into account the dynamic characteristics of the vehicle, as well as taking into account the maximum coefficient of adhesion of tires with a support coating (for example, the vehicle can accelerate at full load with a maximum acceleration of 0.1g, then the coefficient in table 7 for acceleration mode should be adjusted by 0.1, otherwise the mode will not meet the requirement of representativeness);

- **: the value of the coefficient determines the load as a multiplier to the value of the unsprung mass.

The relative plastic strain δ from Table 7 is determined by the formula (5).

$$\delta = \delta_o - \delta_e \tag{5}$$

where δ_o – relative overal strain, [%]; δ_e – relative elastic strain [%].

The assessment of strength, durability requirements and the calculation of the number of cycles must be carried out according to the principle of forming a sequence of cycles Çunloading –loadingÈ (see Figure 8 – the Ç1 – StaticÈ mode should be used as ÇunloadingÈ).

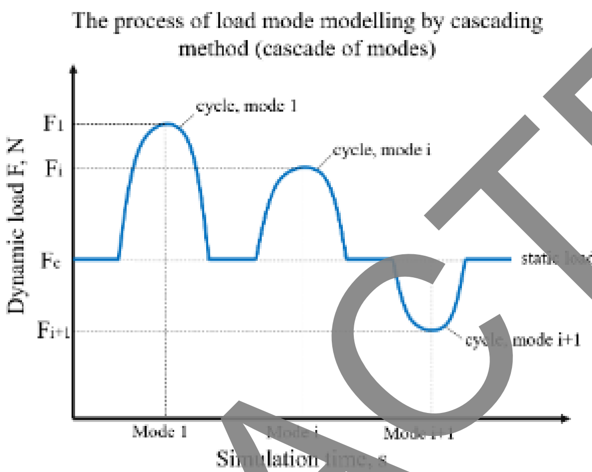


Fig. 8. Modelling process

The requirements for strength and durability in accordance with Table 7 are using separately for each mode. The calculation and assessment of the accumulation of total damage from the action of all modes is not implied. The undercarriage elements of chassis meet the requirements if the calculation results of the cycle count and the accumulated relative plastic elongation separately for each mode satisfy the conditions from Table 7 (simultaneous compliance with the conditions for exceeding the normalized number of cycles and the amount of accumulated relative plastic elongation). It is recommended to apply these modes and requirements at the initial stages of designing category N vehicles (trucks).

The presented results of the work are used in design activities for the development of undercarriage elements of the chassis of category N vehicles in the division of the ÇKAMAZ-BAUMANÈ Research Center at the Bauman Moscow State Technical University and the PJSC ÇKAMAZÈ. Further development of the research work is aimed at testing the applied calculation modes and reliability assessment criteria.

5 Conclusions

1) A proposal has been developed as the cascade of design modes for undercarriage elements of the chassis of a vehicle of category N (trucks) with an indication of the requirements in the form of a minimum number of cycles before failure and the magnitude of relative plastic elongation at the sites of failure, which is an intermediate result in the development of domestic computational methods for modeling strength and durability. The formed cascade of modes takes into account the recommendations that for computational modeling of strength and durability, in addition to vertical loading, it is necessary to use a set of load cases, including longitudinal and transverse loads, as well as their combination.

Without taking into account this nuance, there is a high risk of designing a structure with obviously insufficient strength and durability properties. These conclusions are also closely related to recommendations for the modernization of existing domestic laboratories, the technical equipment of which is still based on compliance with the requirements and performance of work according to the standard [22].

2) Part of the full-scale road tests on the alignment of a category N vehicle (truck) were carried out, which characterize daily operation on public roads in conditions of simulation on the roads of the PJSC ÇKAMAZÈ proving ground. The results obtained are primarily aimed at assessing the requirements of the standards governing the strength criteria of the body components of the drive axles. The results of the study showed that the requirements of the current standard [22] are insufficient (the calculated coefficient of static safety margin corresponds to 3.37, which exceeds the coefficient 2.75 of the current standard [22], normalized for vehicles that are operated mainly on public roads) and are recommended by the authors for revision. The requirements of the previously existing industry standard [21] are more preferable in this regard (the coefficient of static strength reserve corresponds to 4.0, which is closest to the result 3.37). The authors of the article recommend reviewing the coefficient of static strength reserve in the standard [21] in relation to vehicles that are designed for operation mainly on paved roads (operation on public roads), from a value of 2.75 to 3.50 (conservatively rounded).

3) The results obtained in the form of a proposal of a cascade of calculation cases for assessing the properties of strength and durability are used in design activities for the development of chassis elements of trucks of category N in the division of the ÇKAMAZ-BAUMANÈ Research Center at the Bauman Moscow State Technical University and PJSC ÇKAMAZÈ.

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