Method of formation of loading cycles for performing forced bench tests of suspension elements at the stage of technical design

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Abstract. Ensuring the required vehicle service life is one of the most important and topical global engineering challenges. Automobile manufacturers and research engineers around the world are actively working to improve safety and durability testing methods of vehicles, their components and systems. This article touches upon the main issues of comparing the modes of vehicle road operation and the method of forming an adequate program for extreme testing of suspension elements. The developed method has been actively applied in FSUE “NAMI” in the field of research on durability of vehicle components and systems, in particular, of hub units, with the use of mathematical modeling tools and the test base capacities and capabilities.

1. Introduction
A standardized vehicle development procedure includes an engineering design stage, where the safety and durability of individual components of the vehicle running gear shall be checked obligatorily. It is especially important to ensure the sufficient service life of the components, which failure can result in emergencies and accidents during road tests. In a generalized sense, such components include the wheels, hub units, brake control components, guiding device components, chassis load-bearing structure and steering components. A vehicle component service life mostly depends on operating conditions requirements, which are generally defined by the customer and in some cases by the contractor on the basis of statistical road studies [1, 2]. In order to achieve and get the high-quality result of development and check the design safety, effective calculation and experimental methods for design safety and durability check are required. Therefore, improvement of the component assessment methods is a vital and crucial engineering task. Thus, this paper deals with improvement of the domestic methods of hub unit durability and safety assessment.

2. Analysis of known methods for assessing the durability and safety of the hub unit
In the domestic automotive industry, the first groundwork for checking the safety and durability of the hub unit structure is reflected mainly in the methods for performing field tests as part of a vehicle, which establish the volume and conditions of forced field tests at the test proving ground. According to works [3–8], the strength properties of the hubs are assessed by special accelerated tests during the movement of vehicles along a curved trajectory, which is a double or single figure eight. Curvilinear movement of the vehicle generates lateral forces in the contact patch of the wheel with the road, forming bending moments, which lead to a rapid accumulation of damage in the hub unit. However, in this procedure,
the question of the correctness of the conversion factors determining the equivalent vehicle mileage and the consequences of the failure of the hub unit during the tests for the driver remains open.

In the Literature [9, 10], it is noted that the researches have concluded that the hub unit bench tests are reasonable for reduction of time, increase of the results information value and improvement of the test process safety. Figure 1 shows a typical diagram or setup of the test bench for the hub unit safety and durability testing.

The hub unit assy is fixed to the bench equipment in the same way as on the vehicle. The loading devices simulate the radial and axial loading through a suspension knuckle to provide the given bending moment and bearing load. When loaded, the wheel hub is rotated by the e-machine, and upon that the rotation rate determines the required number of the cycles and testing time.

![Figure 1. Schematic diagram of the test bench for testing the hub unit [9, 10].](image)

The analysis of the existing national studies [3–8] on establishing the required time for conducting the tests has shown that the number of loading cycles is generally determined on the basis of the empirical road studies, therefore the justified connection between the loading cycle and the equivalent vehicle run is approximate and needs to be checked. It is also noted that in some cases the researchers choose not to carry out preliminary tests of the hub units of the vehicles being newly developed at the technical design stage, and replace this procedure with the finite element calculation of the hub design with the use of the quasistatic loading method.

Nevertheless, methods for assessing the durability and safety of the hub unit are actively used by foreign automakers, and today the most modern test bench allow testing the hub unit in a mud chamber, which, in addition to the hub, allows us to evaluate the durability of the bearing. At the same time, the load spectra are carefully studied and combined in order to bring the loading mode as close as possible to the operation of the hub unit in the vehicle.

To date, modern methods of forming a spectrum of loading on the chassis of a newly developed vehicle, which are based on the methods of scaling the time histories of loading, have been implemented and are actively used abroad. The most developed are the methods of the engineering centers "Porsche Engineering", "Magna Engineering" [11–13] and the institute Fraunhofer LBF" [14, 15]. As a result of scaling, the values of the wheel loads of the original vehicle are adapted to the required values of the loads of the new vehicle. In this case, the load spectrum has an equivalent with the vehicle mileage,
therefore, the test time can be clearly regulated. It shall be noted that such methods are used by foreign researchers exclusively for the initial verification of the safety and durability of the design. Since the knowledge on the methods of testing the strength and safety of the hub unit at the early stages of the vehicle design is not sufficiently developed and systematized, it is proposed to develop an integrated methods based on the developed theory of scaling the wheel loads by FSUE "NAMI" to form the loading spectrum.

3. Description of the proposed method for assessing the safety and durability of the hub unit

A general view of the hub unit with an indication of the main components included in it is shown in Figure 2.

According to the road studies, the weakest components of the hub unit are the hub and bearing. However, it shall be understood that failure of the hub unit due to a broken wheel hub causes much more serious consequences than failure of the bearing. The proposed methods is based on the study of the stress-strain state of the wheel hub. Below is a sequential list of work required for an initial assessment of safety and durability of the hub design of the newly developed vehicle.

1) Analysis of the stress-strain state of the finite element model of the hub in order to determine the stress concentrators by the method of quasi-static loading.

2) Based on the results of quasi-static analysis, the place of concentration of the highest stresses is determined and the dependence of the stress on the action of the bending moment on the hub is compiled.

3) A representative hub loading cycle is formed for a newly developed vehicle.

4) The calculation of damage accumulation in the hub concentrator for the formed cycle is carried out. A correctly selected stress concentrator, a representative loading spectrum, the parameters of the Wöhler curve and the damage calculation method allows obtaining approximate information on the possibility of the hub failure, however, a large error does not allow using the calculation method as the only reliable one; therefore, the proposed method implies bench testing.

5) Confirmation of the calculations of durability and verification of the safety of the hub and bearing by the method of bench tests of a series of samples of hub unit is carried out. The test results provide valuable information on necessity to optimize the hub geometry to improve durability, as well as information regulations on replacement on the hub unit at subsequent road tests.
4. Results of approbation of the method for assessing the safety and durability of the hub unit

Within the framework of approbation and verification of the proposed method, FSUE "NAMI" has planned a series of calculations and experiments of hub unit for a newly developed vehicle. Figure 3 shows a general view of the research object - the front suspension hub unit of a newly developed vehicle.

At the moment, within the framework of approbation and verification of the method, the following works have been carried out:

To analyze the stress-strain state, a finite element model of the hub was developed and the analysis of weak areas of the design was carried out using the method of quasi-static loading. Figure 4 shows the results of determining the most loaded place of the hub (a hub concentrator is defined) and with a high probability, a hub breakdown will occur in this hub.

![Figure 3. Hub unit of the newly developed vehicle.](image)

![Figure 4. Illustration of the stress-strain state of the hub.](image)
1) Based on the results of the finite element calculation, a surrogate model (ROM) was built in the form of an analytical expression (1), which determines the relationship between the stress arising in the concentrator and the bending moment applied to the wheel hub.

\[ \sigma_c = 0.0335 \cdot M_b + 160.25 + (0.0915 \cdot M_b - 138.55) \cdot \sin(2 \cdot \pi \cdot \omega_c \cdot t + \phi) \]  

(1)

Where \( \sigma_c \) – fillet stress, [MPa]; \( M_b \) – bending moment, [N·m]; \( \omega_c \) – wheel speed, [rps]; \( t \) – time, [s]; \( \phi \) – phase, [°].

In expression (1), the first part \( 0.0335 \cdot M_b + 160.25 \) determines the static preload of the hub (preload by a nut), and the second part of the expression \( (0.0915 \cdot M_b - 138.55) \cdot \sin(2 \cdot \pi \cdot \omega_c \cdot t + \phi) \) defines the cyclic bending moment loading.

2) An analysis of the known approaches to the assignment of load cycles for checking the durability of the hub was carried out:

2.1) One of the approaches to assigning a test cycle to the hub unit in the conditions of almost complete absence of information for the newly developed vehicle at the initial stage of the vehicle design may be wheel testing methods according to the requirements of UNECE Regulation № 124 [16]. As already noted, the main effect limiting the durability of the hub is the action of the bending moment that occurs when moving along curved paths against the background of wheel rotation. This effect is transmitted from the wheel to the hub unchanged. Therefore, the requirements of UNECE Regulation № 124 in terms of satisfying the durability requirements when tested in bend with torsion can be used to assess the durability of the hub. According to the requirements of UNECE Regulation № 124 the wheel shall meet a specified number of cycles at the bending test with a torsion of 75% and 50% of the maximum bending moment defined by the formula:

\[ M_{b\max} = S \cdot F_v \cdot (\mu \cdot r_{st} + d) \]  

(2)

Where \( S \) – safety factor taken equal to 2.0; \( F_v \) – the maximum declared load-bearing capacity of the wheel, i.e. the static load per wheel; \( \mu \) - coefficient of friction between tire and asphalt, taken equal to 0.9; \( r_{st} \) – static wheel radius; \( d \) – wheel offset taking into account the sign.

According to UNECE Regulation 124, Table 1 shows the load cycle requirements for a wheel bending torsion test:

| Parameter | Material value | Steel | Other materials |
|-----------|----------------|-------|----------------|
|           | Material value |       |                |
|           | Vehicle category | M1 and M1G | O1 and O2 | M1 and M1G | O1 and O2 |
| Minimum number of load cycles at 75 % \( M_{b\max} \) | 2,00 \( \cdot \) 10^5 | 0,66 \( \cdot \) 10^5 | 6,00 \( \cdot \) 10^4 | 2,00 \( \cdot \) 10^4 |
| Minimum number of load cycles at 50 % \( M_{b\max} \) | 1,80 \( \cdot \) 10^5 | 0,69 \( \cdot \) 10^6 | 6,00 \( \cdot \) 10^5 | 2,30 \( \cdot \) 10^5 |

Table 1. Requirements for load cycles for wheel testing according to UNECE Regulation № 124

Considering that the hub shall provide the specified durability regardless of the type of wheels installed on it, the maximum values for the corresponding values of the moment and categories of vehicles can be taken as a requirement for assessing the durability. However, it shall be noted that the approach, based on the requirements of UNECE Regulation 124, requires adaptation and verification for calculating the hub unit for the following reasons:

- formula (2) normalizes the fixed value of the safety factor equal to 2.0 unreasonable for the hub;
- formula (2) does not take into account the friction ellipse formed by the longitudinal and lateral forces in the contact patch of the wheel with the road, as a result of which the value of the maximum bending moment is determined to be overestimated;
- formula (2) normalizes the value of the maximum friction coefficient of 0.9, which is also an unreasonable value for the hub, since the normalization of this value excludes taking into account the variability of the operational properties of various vehicles;

- the use of the static radius value in formula (2) is incorrect, since this solution excludes taking into account the nonlinear properties of the tire during curvilinear movement of the vehicle;

- the rationale for the number of loading cycles depending on the value of the bending moment and the variability of the number of cycles depending on the wheel material and bending moment is not obvious, which raises additional doubts about the use of this information to assess the durability of the hub design;

- according to the performed theoretical analysis, an inconsistency in the values of the damaging effect was found when comparing the modes at (0.5 x Mmax) and (0.75 x Mmax), the difference in the damaging effect reaches 95% for the category of steel structures;

- according to the performed theoretical analysis, the maximum bending moment determined by formula (2) is 20% higher than the value of the bending moment calculated by a more accurate method of quasi-static analysis taking into account the nonlinear properties of tires;

- according to the theoretical analysis, the overestimated value of the bending moment during the test mode (0.75 x Mmax) leads to the operation of the hub in the areas of low-cycle fatigue, which causes an excess of the total value of damage to 200% (the calculation was carried out for the value of the bending moment calculated according to the requirements of UNECE Regulation № 124, and for the value calculated by the method of quasi-static analysis).

Thus, when using the approach according to the requirements of UNECE Regulation № 124 to study the durability of the hub unit in its original form without adaptation, there is a possibility of obtaining results that can lead to inappropriate optimization of the hub design and unrepresentative design checking. However, in spite of the indicated approximations and doubts, the considered approach shall be taken into account and taken into account in the comparative study.

2.2) Another method of assigning a test cycle for checking the durability of a hub unit in conditions of almost complete absence of information on the newly developed car at the initial stage of vehicle design can be a method based on the results of empirical studies of forced field tests. For the formation of the hub loading cycle, the analysis of the results of the previously conducted proving ground studies devoted to checking the strength of the wheel hubs was carried out. The cycle formation approach provides for the identification of modes with different values of lateral acceleration and counting the number of cycles for each mode (1 cycle = 1 wheel revolution). Figure 5 shows the generated test cycle, according to the empirical research data of FSUE "NAMI". This approach was previously used by JSC AvtoVAZ to gain experience in the area of development of methods for the transition from road studies of the durability of the wheel hub unit to bench tests.

It shall be noted that even if there are reasonable conversion factors for operating modes between public roads and proving ground roads, this method is very approximate for the following reasons:

a) The calculation of the number of cycles for one mode is determined by formula (3) as the ratio of the number of kilometers in the mode to the way that the wheel travels per one revolution.

$$N_m = \frac{S_m}{2 \cdot \pi \cdot r_{st}}$$

Where $S_m$ – mileage per mode, [m]; $r_{st}$ – static wheel radius, [m].

In formula (3), a static radius is used to determine the way that a wheel travels per one revolution, which excludes taking into account the nonlinear properties of tires.

b) Different modes of motion are divided into groups with different intensity of lateral acceleration, which also accumulates inaccuracy in the interpretation of the results. Thus, the results obtained with this approach can also lead to incorrect hub optimization and unrepresentative design validation.
2.3) As described in the introduction, the most advanced methods for assigning a test cycle to the hub unit in the under condition of almost complete lack of information for the newly developed vehicle at the initial stage of the vehicle design are the methods based on scaling of the wheel loads. Since these methods are developed only abroad and are of a confidential nature, the task of developing its own methods becomes relevant.

Currently, FSUE "NAMI" has developed a method for scaling wheel loads, which is undergoing the stage of approbation and verification. Using the accumulated experience in the field of methods for determining the conversion factors between public roads and proving ground, as well as using the developed scaling theory, a loading cycle was formed that meets the specification dynamic properties of the newly developed vehicle, the operational requirements of vehicle movement on various types of roads in various modes and also a link to the target mileage is suggested. When scaling the time histories of loading, the records of wheel loads, determined according to the method of forced tests of FSUE “NAMI”, of a vehicle with the similar approximate mass-dimensional parameters, elastokinematic properties of suspensions, parameters of elastic and damping properties of suspensions, as well as similar operating modes were taken as a base. The loading spectrum contains the cyclic repeatability of the following modes:

- driving on a mountain road with high intensity (lateral and longitudinal acceleration up to 1g);
- maneuver “figure eight” with lateral acceleration intensity up to 1g.

Figure 6 shows the results of adaptation of the time history of loading for the use of the cycle not only for the purpose of the assessment of the durability, but also for the purpose of simulating the modes on the test bench. The adaptation is reduced to the correction of the speed signals of the hub, the bending moments do not require correction.

The considered method of forming the load spectrum is recommended for use only as the most approximate in the conditions of almost complete absence of information on the newly developed vehicle at the initial stage of the vehicle design for the initial verification of the safety and durability of the design. At the subsequent stages of the vehicle design, the loading cycle shall be determined by an experimental method of accumulation wheel loads according to the methods of the forced field tests with reasoned conversion factors between operation on public roads and proving ground, as well as taking into account the variability of combinations of loads modes.

3) Below is the basic information that was used to calculate the damage accumulation. The obtained results of damage accumulation in the concentrator make it possible to form an assumption on the number of hub failures and the estimated mileage before the failure occurs. Material fatigue parameters (Wöhler curve) for durability modeling are shown in Figure 7.
### Figure 5

Load cycle formed by the method of empirical research.
Figure 6. The results of processing time histories of the hub rotation frequency: "a" - correction of transitions; "B" - decrease in oscillation.
Figure 7. Material parameters (Wohler curve).

$\sigma_B$ – tensile strength, [MPa]; $N_B$ – number of cycles before destruction at the tensile strength stress;

$\sigma_{-1}$ – endurance limit, [MPa]; $N_{-1}$ – number of cycles before destruction at endurance limit stress.

Damage in the concentrator is calculated using formula (4).

$$\sum D_{\text{summary},j} = \sum \frac{N_{i,\text{time\_history},j}}{N_{i,\text{woehler\_curve}}}$$

Where $N_{i,\text{time\_history},j}$ – the number of cycles of the i force arising in the j time history; $N_{i,\text{woehler\_curve}}$ – the number of cycles until destruction under the action of the i force in accordance with the Wöhler curve.

To analyze the damage values, MTS RPCpro software was used with the following settings:
- «damage time history» tool (for analyzing time histories);
- «Generic Stress Life / Load Life with RPCIII Mean Correction»– method of analysis;
- «Notch factor» = 1;
- «Noise band (absolut)» = 0;
- «ScaleFactor» = 1;

When analyzing the damageability of time load histories, the mean stress correction method was used, which is based on the Morrow approach (1960). [17]
Whereas the method without mean stress correction assumes elastic behavior of the part, the local approach to the study of stresses also takes plastic effects into account. When investigating the local approach, the equation consists of two components: elastic and plastic. In the MTS RPCpro software, Morrow’s approach is defined to work with local stress and only corrects the elastic part of the equation for the mean stress determined for the observed cycle. This correction approach is applied to the Basquin equation:

- without correction: \( \sigma_a = \sigma_f \cdot (2N_f)^b \)
- with correction: \( \sigma_a = (\sigma_f - \sigma_m) \cdot (2N_f)^b \) (the part of the Morrow equation that defines elastic deformation).

Where \( \sigma_a \) - amplitude of stress, \( \sigma_m \) - mean stress, \( \sigma_f \) - strength limit, \( N_f \) – number of cycles to failure; \( b \) - fatigue factor (Basquin exponent, determines the angle of the Wöhler curve).

4) Below, Figure 8 shows the results of the comparative analysis of the accumulated damage in the stress concentrator of the hub for various load cycles determined according to the methods described above (see item 3). The developed loading cycle shows the results of the accumulation of the absolute level of damage in the fillet (stress concentrator) of the hub above the mode \((0.5 \times \text{Mmax})\) according to UNECE Regulation № 124 and the mode obtained by the empirical method of forming the cycle. However, the mode \((0.75 \times \text{Mmax})\) according to UNECE Regulation № 124 ensures the operation of the hub in the low-cycle life zone, the absolute level of damage is 286,3 [%] higher than the developed mode, which confirms the need to adapt the standardized information of UNECE Regulation № 124 to the study of the durability of the hub unit.

5) Further research is aimed at verification of the developed method of forming the load spectrum (item 3.3) for testing the hub unit for safety and durability, in the conditions of almost complete lack of information on the newly developed vehicle at the initial stage of the vehicle design. At the moment, preparations are underway for conducting bench tests, Figure 9 shows the installation of the investigated hub unit on the bench.

![Figure 8. Comparison of damage levels in the hub for different loading cycles.](image-url)
Thus, the further stage of approbation and verification of the method is to conduct bench tests. As a result of the study, it is expected that the effectiveness of the method is confirmed for implementation in the process of designing hub unit of FSUE "NAMI" at the initial stages of vehicle design. In the future, it is planned to develop this technique to improve the accuracy and reliability of the results.

5. Conclusion
The developed method for checking the safety and durability of the hub unit is an important tool for improving the efficiency of the design process of the hub unit components at the initial stages of the vehicle design. Today the technique is undergoing the stage of approbation and verification at FSUE "NAMI".

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