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ACCELERATED RELIABILITY TESTS OF CHARACTERISTICS OF OFF-ROAD VEHICLES AND THEIR PARTS

Summary

In this paper, the authors present selected information on accelerated reliability tests of special off-road vehicles and their parts. The vehicles were tested in standard operation and on a polygon using accelerated durability tests of the bearings of the vehicles. The paper presents the theoretical basis of accelerated testing of the reliability properties of the parts and the possibilities of calculating the acceleration coefficient. The authors assumed the linearity of the acceleration function, which is proved in practice in most cases. The authors also present the possibility of using a special polygon for accelerated tests.

Key words: *off-road vehicles, bearings, accelerated reliability tests, acceleration coefficient, methodology, polygon*

1. Introduction

Nowadays, it is essential to obtain a sufficient amount of credible information on the reliability of products at all stages of their life, i.e., throughout their life cycle. According to [1-3], reliability is "The ability to perform as and when required". Two notes complement this definition:

- Reliability includes readiness, fail-safety, recoverability (ability to recover from failure without maintenance intervention), maintainability and maintenance assurance, or other characteristics (sub-characteristics) such as durability, safety, storability, etc.
- Reliability is used as an aggregated term for the time-related characteristics of an object's quality.

In some applications, the term RAMS (Reliability, Availability, Maintainability, Safety) is used instead of the term reliability [3]. The reliability of off-road vehicles depends on many factors, the most important of which are:

- the requirements of the vehicle design specification,
- the fulfilment of the specification requirements by the designer and technologist,
- choice of optimum materials, quality of manufacturing and installation,

- operating conditions, optimum vehicle handling, prescribed maintenance, and quality of repairs, and
- the process of incorporating operational knowledge into vehicle design.

Reliability testing of new products in real-life operation is a very long and expensive process, and the necessary information arrives with a delay that greatly reduces its value and usability. Reducing the time and, therefore, the cost of obtaining relevant product reliability information can be achieved through accelerated or more stringent testing. The accelerated test t_T allows the necessary reliability parameters to be estimated in less time than the actual use of the product t, while the following applies: $t_T < t$. The presented accelerated test methodology is applicable to a variety of manufacturing disciplines, but the authors present procedures that have been used repeatedly in the launch of new off-road special-purpose vehicles. Accelerated tests, where the reduction of the time required to obtain the needed information is achieved by increasing the intensity of the failure mechanisms, e.g., by increasing the load, by increasing the intensity of the operating regime in the field, on special roads, and surfaces (vibrations, impacts, impulses, shocks, bending, torsion, cyclic stresses, etc.), by an increase or decrease in temperature, exposure to air humidity, dust, exposure to water or mud when driving in a ford, etc. The actual acceleration can be expressed as an acceleration coefficient (AC), which is the ratio of the technical life under standard use conditions to the technical life under accelerated test conditions. The acceleration coefficient is necessary for the quantitative extrapolation of reliability indicators from the accelerated test environment to the standard use environment ratio. The acceleration coefficient is a function of the hardware (design advancements, modern technology, materials used, overall architecture, etc.). For multiple dynamic stresses (shocks, pulses, and vibrations), temperature changes, and humidity during accelerated tests, the inverse power law is used as a model; see [4-5] for details. For off-road vehicles on wheeled chassis, selected reliability indicators are used in the tactical and technical requirements for failure-free operation and service life [5-7], as shown in Table 1.

Table 1 Tactical and technical requirements for all-terrain wheeled vehicles

Observed characteristic	**Observed quantity**	**Reliability indicator**	**Marking**
Failure-free	Operation time to failure and between failures	Medium time to failure Medium time between failures Probability of failure-free operation Fault stream parameter	$MTTF$, $\bar{t}_1$ $MTBF$, $\bar{t}$ $R(t_1, t_2)$ z(t)
Lifetime	The time of technical life	Medium technical life P-quantile utility life (90% or 99% technical life to general repairs)	$\bar{t}_{lt}$ t_{ltp}

2. Accelerated tests

During the test period t_T, accelerated testing enables us to obtain estimates of the reliability indicators of the tested product throughout its lifetime t, whereas $t \gg t_T$. Depending on how the time is shortened, accelerated tests are divided into more stringent tests (with more intensive load factors), tests with an accelerated time course (with an accelerated model of operation without downtime), and combined tests. For a usable formulation of the mathematical model of the accelerated test, it is first necessary to define the mode (load), the technical lifetime, and the acceleration function [8-10]. The standard operating mode is a vector $X = \{x_1, (t), x_2, (t), \dots, x_n, (t)\}$ characterized by a set of components (components x_1, $i = 1, 2, \dots, n$ are a deterministic function of time, or are random functions) representing the values of the applied load factors, e.g. mechanical loads (power, torque, vibration, stress, etc.), and factors affecting performance and life cycle such as climatic conditions (temperature, dustiness, humidity, air pressure, etc.). If two modes $X = \{x_1(t), x_2(t), \dots, x_n(t)\}$ and $Y = \{y_1(t), y_2\,(t), \dots, y_n(t)\}$ have the same number and type of components and differ in only one of them, all other things being equal, i.e., $x_i(t) = y_i(t), i \neq k,\ x_k(t) \neq y_k(t)$, then such modes can be characterized by their different components $X = x_k(t),\ Y = y_k(t)$. This case is relatively simple and very common in practice [9]. The operating mode X_{OM} is the one in which no component exceeds the limits of the values specified in the technical conditions. An appropriate measure, which is, in practice, a measure of technical life [10], must be introduced to estimate the effect of the operating mode on the failure mechanism processes [11]. Let

$$\omega = F_X(t) \tag{1}$$

be the probability of failure, or the extent of variability of a parameter, or the operating characteristic of the tested product in the mode X, which is the standard operating mode. The argument of the function $F_X(t)$ may be any function of time, the number of load cycles, the number of kilometres driven, the number of hours worked, and the amount of fuel consumed. We will consider the time as a measure of the technical life corresponding to the level ω :

$$T_X^{(\omega)} = T_X^{(-1)}(\omega), \tag{2}$$

where $T_X^{(-1)}(\omega)$ is the inverse function to function $\omega = F_X(t)$.

If level ω is the probability of failure p, i.e., $\omega = p$, then $T_X^{(p)}$ is 100% the quantile distribution $F_X(t)$ of the product lifetime. The concept of technical lifespan allows the formulation of an accelerated mode Z. The mode Z is called accelerated with respect to a mode X if for any level the inequality (3) applies.

$$T_Z^{(\omega)} < T_X^{(\omega)}. \tag{3}$$

Relation (3) defines the acceleration principle, which implies that the possibility of accelerated reliability tests depends on the existence of a functional relationship that links the technical life rates and the mode of operation of the mechanical product [12]. According to relation (2), a functional relationship can be generally considered as

$$T_X^{(\omega)} = \varphi(X, \omega). \tag{4}$$

Equation (4) allows us to formulate another definition. We shall call the acceleration coefficient of the reliability test the function

$$g(X, Z, \omega) = \frac{T_X^{(\omega)}}{T_Z^{(\omega)}}\,. \tag{5}$$

This function expresses the proportion of measures of technical life in the domain of modes E and $X,\ Z \in E$, and it is the link between the two modes for a given level ω. Its existence is a sufficient condition for solving the accelerated reliability test problem. The acceleration function is linear if the time-to-failure distribution $F(t)$ for the mode area considered is the exponential, Rayleigh, gamma, or Weibull distribution. The acceleration function has the following characteristics [10]:

1. $g(X, Z, \omega)$ is a positive function, decreasing according to X and increasing according to Z,
2. for a large category of mechanical products, the test acceleration function does not depend on the mode range E and level ω, i.e.,

$$g(X, Z, \omega) = g(X, Z) = c, \tag{6}$$

where c is the constant that is only a function of the modes X and Z.

This case is linear because, according to (5), the dependence of $T_X^{(\omega)}$ on $T_Z^{(\omega)}$ can be written in the form

$$T_X^{(\omega)} = c \cdot T_Z^{(\omega)} \tag{7}$$

and it represents the line passing through the origin with the directive c. The constant c is called the acceleration coefficient [4], [6], [13-15]. In order to estimate the effect of the accelerated test mode, a measure of technical life is introduced to define the accelerated mode Z. The technical life measure shall be called the corresponding level ω considering the time

$$T_X = \frac{1}{h_x(\omega)}, \tag{8}$$

where h_x is the monotonous function, and ω is the probability of failure in the mode X during the stringent test.

If $h_x(t) = F_x(t)$ is the distribution function and $\omega = q$, then the time t, satisfying the function $F_x(t) = q$, means that $T_x(q)$ represents the 100 q % quantile of the distribution and the distribution function $F_x(t)$. If $h_x(t)$ is the relative change of the mean value of the performance characteristic $v(t)$, it is considered to be a measure of technical life $T_x(\omega)$ and time t; in this case, equation (9) applies.

$$\omega = \frac{E\{v(t)\} - E\{v(0)\}}{E\{v(0)\}}. \tag{9}$$

The intensity of the failure mechanism in the accelerated test is based on the fact that one or more components of the modes are amplified compared to actual operation, which leads to an increase in the wear rate, acceleration of physicochemical processes, and an increase in the frequency of operation of some mechanisms. The optimal selection of the individual mechanism components and the corresponding modes is the most important task in determining the accelerated test methodology [11], [18]. The selection of the service life indicator is based on the ratio of the mean technical service lives of the vehicle (group, aggregate, and component) in normal operation and in the polygon tests, as follows:

$$q = \frac{E}{E_Z}, \tag{10}$$

where E is the mean technical service life of the vehicle (group, aggregate, and component) under normal operating conditions, E_Z is the mean technical service life of the vehicle (group, aggregate, and component) when tested on the polygon.

These two quantities refer to the operation of the same vehicle in different conditions, while their inherent reliability is the same; therefore, the probability of failure is the same and the following applies: $P(T, t) = P_Z(T_Z, t_Z)$. The distribution function (probability of failure) $F(t)$ of the occurrence of the monitored reliability sub-parameters during the time t in normal mode is as follows:

$$F(t) = F_Z(t_Z), \tag{11}$$

where $F_Z(t_Z)$ is the distribution function (probability of failure) of the division of the observed reliability sub-parameter during the time t_Z in the accelerated test mode.

The accelerated test methodology is based on knowledge of the laws associated with the operation of the product in different modes. An estimate of the reliability of a mechanical product in a given mode can be obtained by transforming the above relations and concepts when moving from one mode to another by means of a mathematical model. The model describes the behaviour of the product in terms of the technical life of the product in the operating and test modes [16-17]. We will introduce such a model on the basis of the principle that, in the domain of modes, the reliability of the product depends on the extent of the reduction of the technical life but does not depend on how this reduction occurred. A typical example of such products is mobile equipment, or, in our case, off-road vehicles. This principle is called the physical principle of reliability and can be expressed by the following equation:

$$F_X(t_X) = F_Z(t_Z). \qquad (12)$$

If a mechanical product operates in the mode of a step change in force, temperature, or load speed, relation (13) applies.

$$x = \begin{cases} x_1 \text{ pro } & 0 \le t < t_1 \\ x_2 \text{ pro } & t_1 \le t < t_1 + t_2 \\ x_n \text{ pro } & \sum_{i=1}^{n-1} t_1 \le t < \sum_{i=1}^{n} t_i \end{cases} \qquad (13)$$

In relation (13), $i = 1, 2, \dots, n$ at each level. The physical principle of reliability can be expressed quantitatively as

$$T_Z^{(\omega_k)} = t_1 g(X_i, \mathrm{Z}, \omega_1) + \sum_{i=1}^{k} \left\{ T_X^{(\omega_1)} g(X_i, \mathrm{Z}, \omega_i) - T_X^{(\omega_{1-1})} g(X_i, \mathrm{Z}, \omega_{i-1}) \right\} \qquad (14)$$

The relation (14) is obtained from the condition of equality of levels when moving from stage to stage, i.e.,

$$\omega_i(T_{Xi}) = \omega_j(T_{Xj}), \qquad (15)$$

which is a modified expression of equation (12), and for the linear case relation (14), it is simplified to the form

$$T_Z^{(\omega_k)} = \sum_{i=1}^{k} t_i g(Z, X_i) \;, \qquad (16)$$

where t_i is the duration of the test in mode X_i, and $\sum_{i=1}^{k} \frac{t_i}{T_{Xi}^{(\omega_k)}}$ applies.

It is known from practice that for a large number of products, linear relationships apply when performing accelerated tests [17], [19]. If linear relationships are valid in the field E, then one set of test products is always tested in the accelerated mode $Z \in E$. At the same time, a second set of analogous products is tested by one of the following methods [20-21]:

Method 1

Until the level ω_1 is reached in the mode $X \in E$ corresponding to the operating conditions, we estimate the acceleration coefficient from relation (7) for the levels ω_1, respectively ω_i. The method can be refined by running the test in mode X up to the levels $\omega_1, \omega_2, \dots, \omega_k$, for $k < n$ and by calculating the average acceleration coefficient from the relation below:

$$\bar{c} = \frac{1}{k} \sum_{J=1}^{k} c_j \;. \qquad (17)$$

Method 2

Assuming that the time to failure distribution $F(t)$ for both modes $X, Z \in E$ is given by two-parameter Weibull's distribution, the distribution function will be considered as

$$F_X(t_X) = \exp\left[-\left(\frac{t_X}{d_X}\right)^{b_X}\right], \tag{18}$$

for the operating mode X, and

$$F_Z(t_Z) = \exp\left[-\left(\frac{t_Z}{d_Z}\right)^{b_Z}\right], \tag{19}$$

for the accelerated mode,
where t is the time ($t > 0$), is the shape parameter ($b > 0$), and d is the scale parameter ($d > 0$).

After substitution, the relations $q = t/t_Z$ and $q = d/d_Z$ apply, and since off-road vehicles are not monitored for the running time but for the number of kilometres travelled, the following relation applies:

$$q = \frac{D}{D_Z}, \tag{20}$$

where D is the number of kilometres travelled over the lifetime of the vehicle under normal operating conditions, and D_Z is the number of kilometres travelled over the lifetime of the vehicle during the test modes.

The shape parameter $b = \frac{y-q}{x}$ corresponds to the direction of the straight line and the scale parameter $d = \exp\left(-\frac{q}{b}\right)$; for details, see [20]).

It is convenient to use empirical data from tests arranged in an ascending series, where the smallest value of the series is the shortest time to failure, and subsequently use them to estimate the median order $F_i(m)$ as follows:

$$F_I(m) = \frac{n_i - 0.3}{n + 0.4}, \tag{21}$$

where n_i is the serial number of the failure from an ordered ascending series, and n is the total number of failures.

Assuming the validity of the physical reliability principle (12) and considering relations (18) and (19), we obtain

$$\left(\frac{t_X}{d_X}\right)^{b_X} = \left(\frac{t_Z}{d_Z}\right)^{b_Z}. \tag{22}$$

For the assumption of linearity to be valid, the parameters of the shape distribution must be equal, i.e., $b_X = b_Z$, so that

$$\frac{t_X}{d_X} = \frac{t_Z}{d_Z}. \tag{23}$$

According to the definition of the test acceleration function, the linear case of equations (5) and (6) is therefore

$$c = \frac{t_X}{t_Z} = \frac{d_X}{d_Z}, \tag{24}$$

which means that the acceleration coefficient c can be estimated using the scale parameters of both distributions, assuming that the argument values of both sets are not transformed.

It follows from the above:

- The shape parameters of two-parameter Weibull's probability distribution obtained from normal operation and accelerated tests are identical (Equation 12).
- The acceleration coefficient of the reliability test is given by the ratio of the scaling parameters of two-parameter Weibull distribution from normal operation and from accelerated tests, equation (24).

3. Accelerated durability test of bearings

According to method 1, a series of accelerated durability tests were performed on 6206-2RS1/C2 SKF bearings [22], which are used in off-road vehicles. A total of six sets of twenty bearings were tested under the same conditions and variable loads L; normal load corresponds to $L_0 = 500$ N, $L_1 = 950$ N, $L_2 = 1450$ N, and $L_3 = 2700$ N. One set of bearings was tested under loads of L_0 to L_2,, and three sets were tested under load L_3. The test ended when the fifth bearing failed. It is known from practice that the technical life of a bearing can be described by two-parameter Weibull's distribution with a constant shape parameter; therefore, a linear model of the acceleration function can be considered. Level ω is the percentage of bearings that failed during the test. The values of acceleration constants c_{ij} for $i = 1, 2, .., 5$, calculated for the levels $\omega_1 = 5\%$, $\omega_2 = 10\%$, $\omega_3 = 15\%$, $\omega_4 = 20\%$, and $\omega_5 = 25\%$ for the loading L_j, $j = 1, 2, 3$, using relation (7), are given in Table 2. For the accelerated modes, the average values of the acceleration coefficient $\bar{c_j}$ can be calculated using equation (17); these values are given in Table 3. Since the loading $L_3 = 2700$ N, a total of three sets were tested; from the test results, the average value $\bar{c_3}$ was calculated. The dependence of the quantities $\bar{c_j}$ and L_j as a function $\bar{c} = f(L)$ shown in the graph in Fig. 1 is very interesting.

It is reasonable to assume that this dependence is expressed as $\bar{c} = a \cdot L^b$, because for $L \to 0$, $T_Z^{(\omega)} \to \infty$, and, therefore $\lim_{T_Z^{(\omega)} \to \infty} c = 0$. Simultaneously, it is evident that for $L = 500$ N , c must be approximately equal to one, i.e., $c \approx 1$. To estimate the constants a and b it is sufficient to select one point through which the curve should pass, e.g., for the value of $L_3 = 2700$ N, $\bar{c} = 275$. Then, we calculate the constants a and b from the equation $b = \frac{\log\ 275}{\log 2700 - \log 500} = 3.29$ and $\log a = -b \cdot \log 500 = -8.88$; $a = 1.32 \cdot 10^{-9}$. The desired dependence then takes the form $c = 1.32 \cdot 10^{-9} \cdot L^{3.29}$.

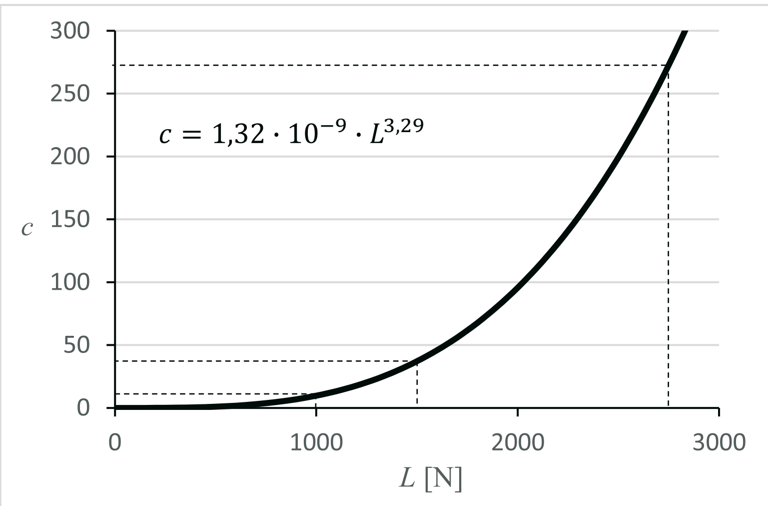

Fig. 1 Dependence of acceleration coefficient on bearing loads

Table 2 Results of accelerated bearing tests for the respective modes

Mode	$X = L_0 = 500$ N	$Z_1 = L_1 = 950$ N		$Z_2 = L_2 = 1450$ N	
Level ω_i (%)	$T_X^{(\omega_i)}$	$T_{Z1}^{(\omega_i)}$	c_{i1}	$T_{Z2}^{(\omega_i)}$	c_{i2}
5	571	72.0	7.93	25.3	22.57
10	574	151.0	3.80	25.3	22.69
15	579	255.5	2.27	25.3	22.89
20	1030	268.0	3.84	31.2	33.01
25	1150	270.0	4.26	35.0	32.86
$\bar{c_J}$	–	–	4.42	–	26.80

Table 3 Results of accelerated bearings tests for the mode $Z_3 = L_3 = 2700$ N

$T_{Z3}^{(\omega_i)}$	c_{i3}	$T_{Z3}^{(\omega_i)}$	c_{i3}	$T_{Z3}^{(\omega_i)}$	c_{i3}
2.41	237	1.96	291	0.97	589
4.10	140	1.96	293	1.95	294
5.45	106	2.70	214	1.95	297
5.45	189	5.43	190	1.95	528
5.45	211	6.11	188	3.15	365
$\bar{c_J}$	177	–	235	–	414
$\bar{c_3}$	275				

Note: *The values of technical life (durability) of the tested bearings,* $T_X^{(\omega_i)}$ *and* $T_Z^{(\omega_i)}$*, are given in* $10^6\ min^{-1}$.

4. Application of the test track for accelerated testing of vehicles

Practice shows that it is advantageous to use special test tracks (polygons) for accelerated tests. The advantages are the stability of test conditions, sophisticated test methodology and organization, safety, the possibility of using special roadways, terrain obstacles, speed and terrain circuits, etc. There are several test tracks in the Czech Republic; the most extensive and significant among them is the test area of the TATRA TRUCKS car factory, Fig. 2 [23], which includes a polygon, specialized workplaces, and laboratories. The polygon consists of a set of special circuits and roadways (speed, terrain, slope, and tipper truck circuits). The special pavements include a paved road, Lydian stone road, Belgian paving, bending, torsion, panel, and block road, cobble pavement, asphalt concrete, and a sinus resonance pavement. The purpose-built pavements consist of a measuring circuit, a lateral stability test road, shallow and deep-water fords, a muddy ford, roads with slopes of 16%, 17%, 22%, 30%, 45%, and 65%, sand section, perpendicular gradients, a ditch, a scratcher road, three road sections, and adhesion roads (sandy, beam, stone, and gravel sections). The laboratories consist of a part strength testing room, an engine testing room, a unit testing room, a laboratory for vibration and noise research, and a chemical laboratory. A T 810 off-road vehicle is shown on the test polygon in Fig. 3, the resonance road in Fig. 4, the torsional vehicle load road in Fig. 5, the block pavement road in Fig. 6, the slope circuit in Fig. 7, the Lydian stone road in Fig. 8, and the scratcher road in Fig. 9. The objective of reliability testing is to verify the performance of the vehicle as a complex vehicle-environment system (road, terrain, load, temperature, humidity, dust, aging of plastics and rubber, wear mechanisms of metals and rubber). The system also includes the driver as the control unit. Off-road vehicles are operated in a wide range of operating, and climatic conditions and types of terrain. The effects of the environment, loading, operating methods, and maintenance have a significant influence on operational reliability. The influence of different sections on the operating load of each chassis group in accelerated polygon tests is shown in Table 4 [11], [17], [20].

Note: *TATRA is the oldest car manufacturer in Central Europe and the second oldest in the world; its foundations were laid as early as 1850 (wagons, hackneys, and railway carriages). The first passenger car, the Präsident, was produced in 1897, and the first truck in 1898.*

Fig. 2 TATRA test site

Fig. 3 Tested off-road vehicle T 810

Fig. 4 Resonance road

Fig. 5 Torsional road

Fig. 6 Block pavement road

Fig. 7 Slope circuit

Fig. 8 Lydian stone road

Fig. 9 Scratcher road

Table 4 Effect of single sections on the operating loads of each chassis group during accelerated polygon tests

Vehicle group	Perimeter section	Terrain circuit	Paved	Belgian	Panel	Lydian stone	Torsion	Bend
Supporting tube	small	medium	medium	medium	medium	small	strong	strong
Frame	small	medium	medium	medium	medium	small	strong	strong
Half-axles	small	medium	strong	strong	medium	small	strong	strong
Springs	small	medium	strong	strong	medium	medium	medium	medium
Shock absorbers	small	medium	strong	strong	medium	medium	medium	medium
Steering gear	small	strong	medium	medium	medium	small	medium	medium
Cab	small	medium	strong	strong	strong	medium	small	small
Accessories	small	medium	strong	strong	strong	strong	small	small

The basic phenomena monitored during the reliability (lifetime) test of an off-road vehicle are failures that result in the removal from service of components, higher units, and ultimately the vehicle as a whole. The general causes of component failure are various mechanisms including adhesion, abrasion, erosion, wear, cavitation, corrosion, ablation, material ageing, thermal degradation, bruising, fracture, deformation, cracks, cracking, and combinations of these wear mechanisms. As for failures of electrical and electronic components, common failure mechanisms are: power overload, dielectric breakdown, electrostatic charge, thermal expansion maladaptation, residual current short circuits, fault arcs, diffusion processes, corrosion of insulators and metals, adsorption, hydrolysis, migration, and software failure due to programmer error. Specific causes of failures in accelerated reliability tests are:

- damage to component shapes, dimensions, and surfaces, cracks, fractures, and permanent deformations due to large accidental overloads, usually under incorrect loading conditions,
- wear of components or contact wear (micro and macro pitting, spalling, galling, scuffing, scoring, mechanical wear, thermal and vibration damage, and abrasive wear) caused by cyclic stress (which occurs typically in rolling bearings, gears, and at the contact point between the cam and the lifter in internal combustion engines).

Proposal of the acceleration coefficient test on the polygon

One of the possibilities for determining (and calculating) the acceleration factor of the test is based on the wear nature of the failures; therefore, the linear theory of wear damage accumulation can be applied. For the numerical expression, knowledge of the load spectra of the chassis groups is required, both in normal operation and on the test polygon, as well as knowledge of the wear characteristics of the component concerned. However, knowledge of the constant characterizing the slope of Wohler's curve is sufficient to determine the acceleration factor. It is assumed that the response of the system does not change significantly and that the interrelationships between the system components and the external load transfer functions are preserved. The measurements are carried out on all sections of the polygon, specifically by traversing selected sections of the test track that have a significant effect on the loading of the chassis groups, as shown in Table 4. The acceleration coefficient c_j for a given group is determined by

$$c_j = \sum v_i \cdot c_{ij} \ , \tag{25}$$

and

$$v_i = \frac{D_i}{D}, \tag{26}$$

where v_i is the track proportion of the individual polygon segments, c_{ij} is the acceleration coefficient of the main chassis groups on the polygon segments, i is the index of the selected polygon segment, j is the index of the selected chassis group, D_i is the distance travelled on the i-th segment [km], and D is the total distance travelled on all selected segments [km].

The value of the acceleration coefficient c_j for a given chassis group can only be influenced by v_i, i.e., the track proportion of the individual load segments, since the values for the individual segments and chassis groups are fixed. The acceleration methodology for the reliability test involves the appropriate specification of each track section v_i to achieve the desired acceleration. The total accelerated test track D on the polygon is determined from the relation

$$D = \frac{D_P}{c_{j\,min}}, \tag{27}$$

where D_P is the distance travelled on the relevant off-road section, $c_{j\,min}$ is the smallest value of the acceleration coefficients of the groups c_j .

The essential task in preparing the accelerated test on the polygon is determining the optimum driving speeds on each segment. High speeds can lead to failures of extremely loaded systems and conversely, low speeds can cause a reduction in the impact of individual sections on the relevant systems. There is no clear recommendation for setting speeds, but the experience of polygon technicians can be used. Their rules imply that the creation of the loading regime on the polygon is based on the technical intuition of the designers.

5. Example of an accelerated test of the off-road vehicles

An accelerated test of T 810 medium off-road trucks was carried out by testing ten vehicles on the road section with a slope of 60%, on unpaved and forest roads with a slope of 25%, and on off-road terrain with a slope of 15%. Two vehicles were tested on the test polygon in off-road and 45% slope modes, in special 35% pavement mode (paved, Lydian stone, Belgian, torsion, bending, and sinusoidal resonance), and 20% purpose-built pavements (lateral stability, gradient, shallow water ford, muddy ford, perpendicular grades). All faults were recorded for the vehicle as a whole and for each group, together with the total number of kilometres travelled and the number of kilometres travelled between failures. The results obtained in the operating are shown in Table 5, and those in the polygon test are shown in Table 6. From the results of the failure rate monitoring found in the literature [18-21], it can be concluded that in both cases the distribution of the times to failure can be described by two-parameter Weibull's distribution of types (18) and (19), respectively, and the shape parameter identity condition applies, i.e., $b_X = b_Z$.

Table 5 Distribution of times to failure of T 810 vehicles in real operation

Serial number of the class	The interval between failures in km	Frequency n_i	Cumulative frequency $n(t_i)$	$F_X(t_i)$	$ln\{-ln[1 - F_X(t_i)]\}$
1	0 – 2000	268	268	0.786	0.433
2	2001 – 4000	44	312	0.915	1.386
3	4001 – 6000	19	331	0.971	1.264
4	6001 – 8000	4	335	0.982	1.391
5	8001 – 10000	4	339	0.994	1.632
6	10001 – 12000	1	340	0.997	1.759

The values of the shape parameter b_X of the scale d_X distribution of the times to failure of ten T 810 trucks in real operation amount to $b_X = 0.89$ and $d_X = 1399$.

Table 6 Distribution of times to failure of T 810 trucks on the test polygon

Serial number of the class	The interval between failures in km	Frequency n_i	Cumulative frequency $n(t_i)$	$F_Z(t_i)$	$ln\{-ln[1 - F_Z(t_i)]\}$
1	0 – 200	123	123	0.640	0.022
2	201 – 400	43	166	0.864	0.691
3	401 – 600	15	181	0.942	1.046
4	601 – 800	11	184	0.958	1.154
5	801 – 1000	3	187	0.974	1.295
6	1001 – 1200	1	188	0.979	1.351
7	1201 – 1400	1	189	0.984	1.419
8	1401 – 1600	1	190	0.989	1.506
9	1601 – 1800	0	190	0.989	1.506
10	1801 – 2000	1	191	0.995	1.667

Note: *In real traffic, we can usually only make very unreliable estimates of the real operating mode in which vehicles are driven (i.e., slope percentage of motorways, class 1 to 3 roads, off-road, unpaved and forest roads, terrain). During the polygon testing, on the other hand, the operating mode is known and we can vary both the load mode by an appropriate selection of test sections and the speed mode by selecting the speed of driving on the test section.*

For quantification of the acceleration coefficient, the above-mentioned method 2 can be used. For the distribution of the times to failure of ten T 810 trucks in operation, the scale parameter $b_X = 0.89$ and the parameter $d_X = 1399.4$. For the distribution of the times to failure of the two T 810 trucks in the polygon tests, the scale parameter is equal to 0.89, i.e., $b_Z = 0.89$, and the parameter *dz* is equal to 222.6, i.e., $d_Z = 222.6$. According to equation (24), the acceleration coefficient will be

$$c = \frac{d_X}{d_Z} = \frac{1399.4}{222.6} \approx 6.3.$$

When testing on a polygon, the corresponding value of the technical life rate is calculated from relation (7), where the $T_Z^{(\omega)}$ values obtained during the tests on the polygon are substituted.

6. Conclusion

The methodology of accelerated testing, briefly described and illustrated by relatively simple concrete examples, provides a theoretical basis for the testing and calculation of the reliability of machinery and shows a practical procedure that has been repeatedly used by the authors. The paper briefly explains the theory of accelerated tests that require conversion to standard operating conditions. For accelerated tests only, the results do not require special conversions to normal operation. However, stringent tests, requiring the construction of a stringent operating model, cannot simply be described in general terms, and each individual case needs to be dealt with separately according to the type and characteristics of the mechanical product being observed and tested.

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