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FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS OF MECHANICAL SYSTEMS' ELEMENTS

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RESEARCH ARTICLE

ABSTRACT: Basic concepts and a brief history of the development of Failure Modes, Effects and Criticality Analysis - FMECA are given in the introductory part of the paper. In the present considerations, the quantitative FMECA is based on the assumption that the intensity of the element's failure is constant and is mainly applied in electronic systems. Based on the current procedure, taking into account the specificity of the mechanical system's elements in terms of the intensity of the failure, the proposal of the quantitative FMECA of these elements is given. The procedure has been expanded with a step of determining the absolute criticality of the elements from the aspect of reliability and functional safety. The application of the procedure is illustrated through the case of determining the criticality of the elements of the light commercial vehicle's steering system based on exploitation data.

KEY WORDS: reliability, quantitative FMECA, steering system, commercial vehicle

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ANALIZA VRSTE OTKAZA, EFEKATA I KRITIČNOSTI ELEMENATA MEHANIČKIH SISTEMA

REZIME: U uvodnom delu rada je prikazan osnovni koncept i kratak istorijski razvoj analize vrste otkaza, efekata i kritičnosti (eng. Failure Modes, Effects and Criticality Analysis) – FMECA. U dosadašnjim razmatranjima, kvantitativna FMECA zasniva se na pretpostavci da je intenzitet otkaza elemenata konstantan i uglavnom se primenjuje kod elektronskih sistema. Na osnovu postojećeg postupka, uzimajući u obzir specifičnosti elemenata mašinskih sistema u pogledu intenziteta otkaza, dat je predlog kvantitativne FMECA ovih elemenata. Postupak je proširen korakom za određivanje apsolutne kritičnosti elemenata sa aspekta pouzdanosti i sigurnosti funkcionisanja. Primena postupka je ilustrovana na primeru određivanja kritičnosti elemenata sistema za upravljanje lakih teretnih vozila na osnovu podataka iz eksploatacije.

KLJUČNE REČI: pouzdanost, kvantitativna FMECA, sistem za upravljanje, teretno vozilo

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1. INTRODUCTION

Failure Modes and Effects Analysis (FMEA) is one of the basic and the most used method for analysing the safety and reliability of technical systems [1, 2, 3]. Efficiency of FMEA method application is the greatest if used in the phase of design by multi-disciplinary team of experts. FMEA is generally an inductive (bottom – up) method. It is based on consideration of all potential failures of constitutive parts of the system and effects they have on the system. Criticality Analysis (CA) is a procedure for evaluation of criticality rating for all constitutive parts, where, by criticality, a relative measure of item's failure modes influence on reliable and safe operation of the system is meant. Joint FMEA and CA analysis are called Failure modes, effects and criticality analysis – FMECA [4].

FMECA was developed for USA military purposes as a technique for assessment of reliability through determination of effects of different failure modes of technical systems [3]. This method dates from November 9th, 1949, as an official document in a form of an American military standard, denoted as MIL-P-1629 [5], titled 'Procedures for Performing a Failure Mode, Effects and Criticality Analysis'. Outside the military, FMEA began to be used in the aircraft and space industry. During the fifties and sixties, airline company Boeing has developed FMEA method and became one of its creators. NASA in 1966 had published its procedure for FMEA, which was used in the Apollo program [6].

Although FMEA is considered an useful tool for improving product quality, this method is beginning to be used in the automotive industry only in the early seventies. In 1971 Ford Motor Company introduces an internal standard that refers to the FMEA method. The Automotive Industry Action Group (AIAG) and the American Society for Quality Control (ASQC) copyrighted industry wide FMEA Manuel in February of 1993 [7].

Considering the content of publications that were developed later and related to the FMEA method, it can be concluded that the MIL-P-1629 standard and its revised version MIL-STD-1629A from 1980 [8], represent the basis for the part referring to the quantitative FMECA. Motor vehicle's steering system is a mechanical system that has to meet high demands regarding reliability [9, 10]. Importance of the motor vehicle's steering system for human safety requires a detailed analysis of structural components in view of occurrence of their failure during exploitation. For the failure analysis of the considered device, it is necessary to know the structure, way of operating, working conditions and all factors that have a greater or less influence on its reliability.

2. QUANTITATIVE FMECA

Analysis of the modes, effects and criticality of failures of technical systems' elements can be done qualitatively or quantitatively, depending on whether the data on failure intensity of elements are known [5, 8]. FMECA quantitative procedure is based on exploitation data (mostly electronic elements), if the intensity of failures is known or can be assessed, is implemented in three steps [1, 8, 11, 12, 17]:

1. Determination of criticality C_{ij}^k of failure mode *j* of element *i* is to be done by categories of failure effects *k* (*k* = 1, 2, 3, 4), using [1, 8, 12, 18]:

$$C_{ij}^{(k)} = \alpha_{ij} \cdot \beta_{ij}^{k} \cdot \lambda_i \cdot t_i \tag{1}$$

where:

α_{ij} - relative rate (frequency measure) of failure mode j of element i, ($0 \leq \alpha_{ij} \leq 1$, $\sum_j \alpha_{ij} = 1$)

β_{ij}^{k} - conditional probability that failure mode j of element i will cause category k failure effect according to the adopted classification (values are taken orientationaly from Table 1, according to recommendations from [1, 8, 11, 17, 18],

$\lambda_i = \sum_j \lambda_{ij}$- failure rate of element i (primary source of failure rate data for electronic part and values of influencing factors is MIL-HDBK-217F [19],

λ_{ij}- part failure rate of mode j of element i, and

t_i - operating time of element i.

Table 1. Guideline values failure effect probability

Failure effect description	Probability value of $\beta_{ij}^{(k)}$ [-]
Actual loss	1.00
Probable loss	0.10 < < 1.00
Possible loss	0 < ≤ 0.10
No effect	0

Calculated values of C_{ij}^{k} apart from being the starting point for determination of other quantitative properties of element's criticality, they make it possible to rank the element's failure modes according to effects in order to evaluate the most critical system's failure modes from the aspect of reliability and safety.

2. Determination of failure criticality of element i, which causes the k-th category of failure effects [1, 8, 17]:

$$C_i^{(k)} = \sum_j C_{ij}^{(k)} \tag{2}$$

Calculation of $C_i^{(k)}$ enables the isolation of the most important elements whose failures lead to certain categories of effects.

3. Determination of criticality of the k-th category of the system's effects, by summation of criticalities of all elements failure modes for the specified effect category [17]:

$$C_k = \sum_i \sum_j C_{ij}^{(k)} \tag{3}$$

Calculated values of C_k are statistical indicators of the representation rating of the individual category of effects.

According to standard of International Electromechanical Commission IEC 60812 [12], 'the major deficiencies of this approach are the implicit assumption of constant failure rate and that many of the factors are predictions or best guesses only. This is especially the case when the system components cannot have an associated failure rate, just the calculated failure probability for the specific application, its duration, and associated stresses, such as mechanical components and systems'.

3. QUANTITATIVE FMECA PROCEDURE FOR MECHANICAL SYSTEMS' ELEMENTS

Depending on the behavior of intensity of failure function *h(t)*, the entire exploitation life of mechanical parts can be divided into three periods (Figure 1) [13]: the initial period (high intensity of failure with a tendency to sudden decrease), the period of normal operation (intensity of failure is approximately constant) and aging period (intensity of failure is an increasing function of time).

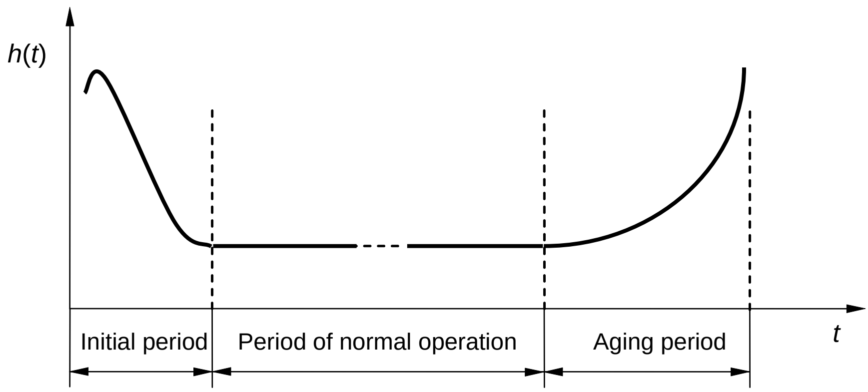

Figure 1. The intensity of failure of mechanical systems' elements as a function of operating time

The question is: What value of intensity of failures and from which the period of operation should be taken to determine the criticality of elements that will equally represent all modes of failure of elements in the entire service life? This dilemma is particularly evident if one considers that there are elements with the failure modes are characteristic only for certain periods of operation. In addition, unlike the exponential distribution for other distributions of intensity's failure is a complex function of time, which depends on several parameters (e.g., the Weibull distribution, depending on the model, there are two or three parameters). Determination of functional dependence and the parameters of the distribution require a detailed examination of elements for the assessment of reliability.

Ultimately, if you know the functional dependence of $h(t)$, then the criticality of an element must be the same function of time. In this way, you would get the criticality as a variable in time. This approach (if there is an objective feature), is interesting for ranking the criticality level of elements in different periods of operation.

Due to the unrealistic images of the degree of criticality, given by the assumption that the intensity of failure of mechanical systems' elements is constant and because of the objective impossibility of determining the intensity of failure as a function of time for every failure mode for each element of the mechanical system, it is established that the intensity of failure of machine elements can't be taken as a failure parameter for calculating the criticality.

Mean time of operation until the failure of an element is an indication of durability, which is relatively easy to determine. It is logical that the criticality of an element is less as time of operation until failure is larger and vice versa. On this basis, we can conclude that the criticality of an element is inversely proportional to the mean operation time until the failure of that element.

Based on the existing methodology for the quantitative FMECA, and taking into account the previous remarks, we developed a quantitative procedure FMECA for elements of mechanical systems consisting of four steps [14, 15, 16, 20]:

1. Determination of criticality of failure mode *j* of element *i* is to be done by categories of failure effects *k* (*k* = 1, 2, 3, 4), using [21]:

$$C_{ij}^{(k)} = \frac{\alpha_{ij} \cdot \beta_{ij}^{(k)} \cdot t_i}{t_{sr_{ij}}} \tag{4}$$

Unlike the meaning of α_{ij} in expression (1), there are many elements of mechanical systems in which failure occurs only in a relatively small number of systems throughout the entire service life. Therefore, in order to have a realistic criticality assessment, in this case α_{ij} represents a relative share of the failure mode of an element in all systems.

Tags $\beta_{ij}^{(k)}$ and t_i have the same meaning as in equation (1), and $t_{sr_{ij}}$ is mean operating time to failure of mode *j* of element *i*.

$t_{sr_{ij}}$ represents the average working time until the failure mode *j* of element *i* occurs.

In general, mean operation time to failure of element is the mathematical expectation of random variable of operation time to failure. For a set of measured values of a random variable, the mean operation time to failure is equally arithmetic average of the obtained results:

$$t_{sr} = \frac{1}{n} \cdot \sum_{i=1}^{n} t_i \tag{5}$$

where:

n - total number of results, and

t_i - time until the failure of the element *i*.

2. Determination of failure criticality of element *i*, which causes the *k*-th category of failure effects, according to expression (2).

3. Determination of 'absolute criticality' of element *i* according to [15, 16, 20]:

$$C_i = a_1 C_i^{(1)} + a_2 C_i^{(2)} + a_3 C_i^{(3)} + a_4 C_i^{(4)} \tag{6}$$

where:

a_k- 'weight' of the *k*-th (*k* = 1, 2, 3, 4) category of effects (values may be determined using subjective evaluation of effect's 'weight' for each case, from the interval between 0 and 1) and

$C_i^{(k)}$- the *i*-th element criticality for the *k*-th category of effects.

This step is an extension compared to the starting method FMECA. The idea is to assign each category of effects corresponding 'weight' in proportion to the importance of effects. For example, the system that would have four categories of effects, which are defined so that the effects of category one are most serious, and the effects of category four are easiest, the 'weight' factors of category of effects can be adopted as follows:

$a_1 = 1.00; a_2 = 0.75;\ a_3 = 0.40\ and\ a_4 = 0.20.$

4. Determination of criticality category *k* of the system's effects, by summation of criticality of all elements' failure modes for the specified effect category according to expression (3).

Due to the large amounts of data, a quantitative FMECA of elements of mechanical systems is difficult without the use of computers and related software. Therefore, it was established the computer program. By using the program it was performed a quantitative analysis of the criticality's level of steering system's elements for light commercial vehicles.

4. QUANTITATIVE FMECA OF STEERING SYSTEM'S ELEMENTS OF LIGHT COMMERCIAL VEHICLES

Steering system is one of the vital parts of the complex mechanical system called 'motor vehicle' [9]. Together with the braking system and the tires, it has crucial significance for safety of motor vehicles and people in traffic. Thus, great attention is given to demands that are set before the steering system regarding reliability.

In order to determine the critical elements of the restrictive effect on a reliable and safe operation of steering system of commercial vehicles, based on data from exploitation, the quantitative analysis of modes, effects and criticality of failure of this system's elements is performed. Basis for this analysis was a complex data structure in the form of a table data sheet. Procedure for data acquisition needed for quantitative FMECA of the light commercial vehicle's steering system consisted of the following steps [14]:

1. Structural system division, identification and coding of constitutive elements of the light commercial vehicle's steering system was carried out on the basis of the technical documentation of the vehicle's manufacturer by forming a structural block diagram [22];

2. The adoption of structural level for conduction of analysis of criticality (It is accepted that the quantitative method FMECA should be conducted at the lowest level of replaceable units in the steering system);

3. Identification and recording of the most failure modes of steering system's elements were done by forming the fault tree [23];

4. Determination of relative participation of individual element failure modes;

5. Category definition of final failure effects. All failure mode effects of the steering system's elements are classified in four categories:

k.1 - effects which threatened the safety of people and vehicles due to the immediate termination of performing the functions of the system

k.2 - there is the possibility of performing an interruption of steering system's function after a while, if the failures are not eliminated

k.3 - output and input parameters of the system are beyond the permissible limits (the appearance of increased clearance, required torque on the steering wheel is larger than normal or abnormal geometry of the wheels due to deformation of a lever mechanism of steering system) and

k.4 - changes to the system's elements that do not significantly influence the functioning and can have serious effects, and changes that, if not remedied, may lead to the emergence of modes of failure with the effects *k*.3.).

6. Categorization of element's failure modes according to effects and determination of conditional probabilities of final effects occurrence was done with the help of technical personnel services for the maintenance of the considered type of vehicle (Conditional probability of occurrence of final effects of element's failure modes are determined by subjective evaluation based on Table 1)

7. Determination of mean operating time until element failure occurs (Systems and elements of motor vehicle are loaded with variable loads in the course of time. The total number of load variation cycles is proportional to distance passed. Thus, time until failure of the most elements of motor vehicles occurs is measured in kilometres of distance passed.) and

8. Calculation of the total operation time of elements. Operation time of steering system's elements of motor vehicles t_i is the same for all elements and has no effect on the relative criticality of failure modes of elements. Therefore, when calculating the criticality it was taken as unit of time.

Forming of input files for the program of quantitative FMECA of mechanical systems' elements was performed based on the data, which one part is shown in Table 2. To calculate the elements absolute criticality in accordance with (6), the following weighting factors of effect categories are adopted: $a_1 = 1;\ a_2 = 0.5;\ a_3 = 0.3\ and\ a_4 = 0.2$. Weighting factors were adopted by subjective assessment of the experts from the subject area.

Designation Q in Table 2 is for quantity or number of identical elements within the scope of discussed object of analysis.

By processing of the acquired data given in Table 2, by using the computer program for quantitative FMECA of mechanical system's elements, the results are obtained for:

- criticality of the steering system elements' failure modes without taking into account the effects (Table 3)
- criticality of the steering system elements' with taking into account the effects (Table 4)
- absolute criticality of the steering system elements' (Table 5) and
- criticality of final failure effects of the steering system elements' (Table 6).

Table 3 contains the initial part of the output results of the program obtained by criticality ranking of a total of 49 different steering system elements' failure modes regardless of the result. Based on Table 3, the top two places by criticality occupy increased clearances in a tie-rod's ball joints. Criticality of the longitudinal tie-rod with ball joint is determined by the criticality of the tie-rod's ball joint. Thus was obtained about the same level of criticality of both the assembly. Increased clearance in tie-rod joints most frequently occurs in aging period, due to wear of sliding surfaces of the ball pin and the cup. An influence may be exerted on the increase of mean operating time until the increased clearance in the joint occurs or on reduction of a tie-rod joint's criticality by the increase of material's or surface layer's resistance to wear, by better lubrication and by better protection from the influence of the environment.

On the third and fifth place by the criticality are failure modes of steering shaft's bushings. Increased clearance and cracking of bushes occur during aging period due to wear. The failure of bush is primarily reflecting the occurrence of vibration on the steering wheel. In fourth place by the criticality is cracking the rubber insert of coupling. The failure occurs due to aging and loss of elasticity of rubber. It is manifested in the appearance of the visible clearance in coupling and delay of output effects of systems on steering wheels with respect to the input effect on the steering wheel.

Table 2. Part of the base of the FMECA procedure for elements of the steering system of light commercial vehicles

Element's name	Elem. code	Q [-]	Failure mode	Failure mode code	Rel. rate α_{ij} [-]	Loss prob. $\beta_{ij}^{(k)}$ [-]	Final effect	$t_{sr_{ij}}$ [km] x103
Steering wheel	61001	1	Damage Insufficient tightening of screws	N.06 N.31	0.002 0.001	1.0 0.1	*k*.4 *k*.2	20 3
Steering shaft	61002	1	Radially throw Damage of the groove for connection	N.02 N.07	0.0002 0.03	1.0 0.4	*k*.4 *k*.3	3 200
Steering shaft bracket	61004	1	Insufficient tightening of screws Cracking at weld	N.31 N.69	0.0002 0.0005	1.0 0.8	*k*.3 *k*.3	30 100
Steering shaft bushing	61005	1	Cracked bushes Increased clearance	N.06 N.35	0.3 0.7	1.0 1.0	*k*.3 *k*.3	200 100
Steering head support	61006	1	Cracking Insufficient tightening of screws	N.06 N.31	0.0005 0.0002	0.8 1.0	*k*.1 *k*.3	300 30
Rubber insert	61011	1	Cracking	N.06	1	1.0	*k*.3	200
Housing of the steering head	61101	1	Damage of the cover sealer Porosity of the case	N.37 N.81	0.01 0.008	0.7 0.3	*k*.4 *k*.4	200 15
Worm shaft	61103	1	Damage of the teeth Cracking - fracture Damage of grooves	N.05 N.06 N.07	0.006 0.0005 0.001	1.0 1.0 0.8	*k*.3 *k*.1 *k*.3	300 350 200
Roller bearing of the steering head	61104 61105	1 1	Bearing damage No adjustment of the clearance	N.11 N.62	0.006 0.003	1.0 0.7	*k*.3 *k*.3	350 400
Shaft with segment	61110	1	Damage of the teeth Cracking - fracture Damage of grooves No adjustment	N.05 N.06 N.07 N.62	0.006 0.0005 0.001 0.005	1.0 1.0 0.6 1.0	*k*.3 *k*.1 *k*.3 *k*.3	300 350 200 30
Sliding bearing of the output shaft	61107	2	Bearing damage	N.11	0.01	1.0	*k*.3	350
The lever of the longitudinal tie-rod with ball joint	62110	1	The deformation of the lever Cracking - fracture Damage of the thread Loose connections Increased clearance	N.02 N.06 N.07 N.31 N.35	0.0005 0.0007 0.003 0.001 0.9948	0.6 1.0 0.8 1.0 1.0	*k*.3 *k*.1 *k*.2 *k*.2 *k*.3	30 100 100 15 100
Tube of the transverse tie-rod	62201	1	Damage of the thread Insufficient tightening of the clamping ring	N.07 N.31	0.0001 0.0003	0.8 1.0	*k*.2 *k*.2	10 15

Tie-rod's ball joint	62120 62210 62230	1 1 1	Body joint deformation Fracture of the eyeball or the ball joint's body Damage of the thread Loose connections Increased clearance	N.02 N.06 N.07 N.31 N.35	0.0002 0.0007 0.003 0.001 0.9951	0.3 1.0 0.8 1.0 1.0	*k*.3 *k*.1 *k*.2 *k*.2 *k*.3	40 100 100 15 100

Table 3. Criticality of the steering system elements' failure modes without taking into account the effects

No.	Code	Element's name	Failure mode	Eff. name	α_{ij} [-]	$\beta_{ij}^{(k)}$ [-]	$t_{sr_{ij}}$ [km] x103	t_i [km]	Criticality $C_{ij}^{(k)}$[-]
1	62210	Tie-rod ball joint	Increased clearance	*k*.3	0.9951	1.0	100	1	0.9951E-05
2	62110	The lever of the longitudinal tie-rod with ball joint	Increased clearance	*k*.3	0.9948	1.0	100	1	0.9948E-05
3	61005	Steering shaft bushing	Increased clearance	*k*.3	0.7000	1.0	100	1	0.7000E-05
4	61011	Rubber insert	Cracking	*k*.3	1.0000	1.0	200	1	0.5000E-05
5	61005	Steering shaft bushing	Cracking of bushes	*k*.3	0.3000	1.0	200	1	0.1500E-05
6	61003	Sealer of steering shaft	No hermetic	*k*.4	0.1200	0.4	150	1	0.3200E-06
7	61110	Shaft with segment	No adjustment	*k*.3	0.0050	1.0	30	1	0.1667E-06
8	61101	Housing of the steering head	Porosity of the case	*k*.4	0.0080	0.3	15	1	0.1600E-06
9	61003	Shaft seal	Insufficient tightening of the bolts	*k*.4	0.0030	0.1	3	1	0.1000E-06
10	61001	Steering wheel	Damage	*k*.4	0.0020	1.0	20	1	0.1000E-06
11	61002	Steering shaft	Radially throw	*k*.4	0.0002	1.0	3	1	0.6667E-07
12	62002	Lever on wheels	Loose connection with sleeves	*k*.2	0.0010	1.0	15	1	0.6667E-07
13	62110	The lever of the longitudinal tie-rod with ball joint	Loose connections	*k*.2	0.0010	1.0	15	1	0.6667E-07
14	62210	Tie-rod's ball joint	Loose connections	*k*.2	0.0010	1.0	15	1	0.6667E-07
15	61002	Steering shaft	Damage of the groove for connection	*k*.3	0.0300	0.4	200	1	0.6000E-07
16	61109	Sealing ring	No hermetic	*k*.4	0.0200	0.7	350	1	0.4000E-07
17	61101	Housing of the steering head	Damage of the cover sealer	*k*.4	0.0100	0.7	200	1	0.3500E-07
18	61101	Steering wheel	Insufficient tightening of screws	*k*.2	0.0010	0.1	3	1	0.3333E-07
19	61107	Sliding bearing of the output shaft	Bearing damage	*k*.3	0.0100	1.0	350	1	0.2857E-07
20	62110	The lever of the longitudinal tie-	Damage of the thread	*k*.2	0.0030	0.8	100	1	0.2402E-07

		rod with ball joint							

Table 4. Criticality of the steering system elements' with taking into account the effects

a) Criticality by effects k.1			
No.	Code	Element's name	$C_i^{(2)}$ [-]
1	62210	The lever of the longitudinal tie-rod with ball joint	0.7000E-08
2	62110	Tie-rod ball joint	0.7000E-08
3	61110	Shaft with segment	0.1429E-08
4	61103	Worm shaft	0.1428E-08
5	61006	Steering head support	0.1333E-08
6	62001	Lever on the steering head	0.1333E-08
7	62002	Levers on wheels	0.1143E-08
b) Criticality by effects k.2			
No.	Code	Element's name	$C_i^{(2)}$ [-]
1	62210	The lever of the longitudinal tie-rod with ball joint	0.9067E-07
2	62110	Tie-rod ball joint	0.9067E-07
3	62002	Lever on wheels	0.6667E-07
4	61001	Steering wheel	0.3333E-07
5	62201	Tube of the transverse tie-rod	0.2800E-07
6	62001	Lever on the steering head	0.1667E-07
c) Criticality by effects k.3			
No.	Code	Element's name	$C_i^{(3)}$[-]
1	62110	The lever of the longitudinal tie-rod with ball joint	0.9958E-05
2	62210	Tie-rod ball joint	0.9953E-05
3	61005	Steering shaft bushing	0.8500E-05
4	61011	Rubber insert	0.5000E-05
5	61110	Shaft with segment	0.1667E-06
6	61002	Steering shaft	0.6000E-07
7	61107	Slide bearing of output shaft	0.2857E-07
8	61012	Flange on the worm shaft	0.2567E-07
9	61103	Worm shaft	0.2400E-07
10	61104	Roller bearing of the steering head	0.2239E-07
11	61004	Steering shaft bracket	0.1667E-07
d) Criticality by effects k.4			
No.	Code	Element's name	$C_i^{(4)}$ [-]
1	61003	Sealer of steering shaft	0.4200E-06
2	61108	Housing of the steering head	0.1950E-06
3	61001	Steering wheel	0.1000E-06
4	61002	Steering shaft	0.6667E-07
5	61108	Sealing rings	0.4000E-07
6	61102	Steering head's cork	0.6666E-08

Based on a criticality degree of steering system's elements with taking into account the effects (Table 4), it may be seen that, in severe categories of effects the dominant position occupies failure modes of the lever of the longitudinal tie-rod with ball joint and the tie-rod ball joint, but with relatively small values of criticality. For effect *k*.1, criticality of elements is the order of magnitude of 10^{-8}, and for effect *k*.2, the order of magnitude is 10^{-7}. For effect *k*.3, the top two places are tie-rod ball joints which together with steering shaft bushing and a rubber insert of coupling have the criticality degree of order 10^{-5}. Shaft with segment has a criticality of the order 10^{-6}, while the criticality of other elements is the order of magnitude of 10^{-7}. The degree of critical elements resulted from *k*.4, due to an effect, is not relevant for the determination of critical elements in the system.

By the most critical elements of steering systems can be reached directly, based on the degree of absolute criticality of elements. Table 5 shows the results of the ranking of all 20 elements of the considered steering system according to the degree of absolute criticality. Based on these results, the most critical elements of the steering system, according to the sequence, are the lever of the longitudinal tie-rod with ball joint, the tie-rod's ball joint, steering shaft bushing, etc.

Table 5. Absolute criticality of the steering system elements

No.	Code	Element's name	C_i [-]
1	62110	The lever of the longitudinal tie-rod with ball joint	0.3040E-05
2	62210	Tie-rod ball joint	0.2988E-05
3	61005	Steering shaft bushing	0.2550E-05
4	61011	Rubber insert	0.1500E-05
5	61003	Sealer of steering shaft	0.8400E-07
6	61110	Shaft with segment	0.5144E-07
7	61002	Steering shaft	0.3900E-07
8	61108	Sealing rings	0.3665E-07
9	62201	Tube of the transverse tie-rod	0.3448E-07
10	61012	Flange on the worm shaft	0.3133E-07
11	61101	Housing of the steering head	0.1917E-07
12	62002	Lever on wheels	0.1400E-07
13	61004	Steering shaft bracket	0.9330E-08
14	61001	Steering wheel	0.8628E-08
15	61104	Roller bearing of the steering head	0.8571E-08
16	61006	Steering head support	0.7701E-08
17	61107	Slide bearing of output shaft	0.6717E-08
18	62001	Lever on the steering head	0.5001E-08
19	61103	Worm shaft	0.3333E-09
20	61102	Steering head's cork	0.1333E-10

The other way of determination of the most critical elements of the steering system is a comparative analysis of Table 4 and Table 6. In Table 6, there is an obvious predominant occurrence of elements' failure modes with category of effect equal to three. 96.62% of a total sum of elements 'criticality are elements' failure modes with third category of effects. Table 4 contains the elements ranked by criticality and by category of effects.

Table 6. Criticality of final failure effects

No.	Final effect	C_k [-]	Rel. crit. %
1	*k*.3	0.3363E-04	96.62
2	*k*.4	0.8284E-06	2.38
3	*k*.2	0.3260E-06	0.94
4	*k*.1	0.2067E-07	0.06

Figure 2 shows Pareto analysis of elements' criticality rate of light commercial vehicles' steering system elements with failure modes that have a third category of effects is given. Since the representation of failure modes of elements for the remaining categories of effects is negligible, Figure 2 illustrates also the overall criticality of the elements.

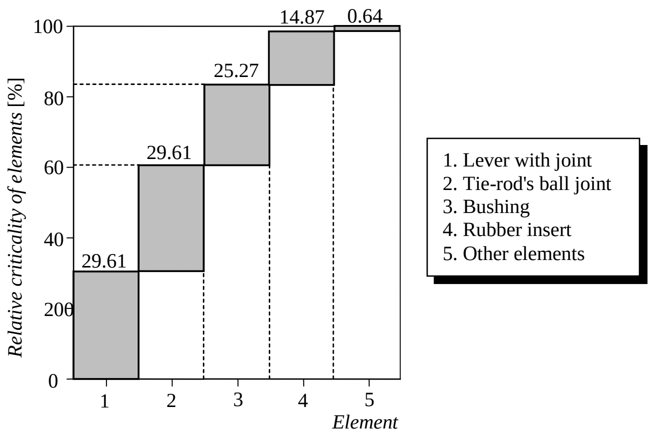

Figure 2. Pareto analysis of criticality rate of elements for category of effects k.3

Based on the results of the program for a quantitative analysis of the degree of criticality and Figure 2, it can be concluded that the most critical elements of steering system in terms of durability and safety are: the lever of the longitudinal tie-rod with ball joint, tie-rod ball joint, steering shaft bushing and rubber insert of coupling. All other elements are within 0.64% of criticality. In this case, Pareto analysis of absolute criticality of steering system elements gives similar results.

5. CONCLUSIONS

The procedure of quantitative FMECA, which is defined by existing standards, can be applied without reservation when the intensity of all modes of failure of elements is constant, i.e. when it is not the function of time, and therefore, characterizes the reliability of elements for the entire period of operation (for example, at electronic elements). However, application of this methodology, in cases_where the intensity of failure as a function of time, (for example, at mechanical elements), can lead to major errors and distortions of real images of criticality of elements. Therefore, a modification of the existing procedure of quantitative FMECA is made in the sense of creating the possibility of applying the method to the mechanical systems. The intensity of the failure, as a functional reliability indication, common to all the failure modes of the element, is replaced by the reciprocal value of the mean time to failure of individual failure modes. In addition, the relative frequency of the failure mode is defined as a part of failure mode for all machine system elements during the service life. This means that in most cases, the sum of relative frequencies is significantly lower than one. By introducing the aforementioned changes, the criticality of the failure mode of elements, which significantly reflects the real state, is obtained.

The procedure of quantitative FMECA of mechanical system's elements contains a step for determining the absolute criticality of the elements. By ranking the obtained values of the absolute criticality, the degree of criticality of system's elements can be directly assessed from the aspect of durability and safety without additional complicated analysis. Calculation of the absolute criticality especially comes to the fore in cases where the relative criticality of failure modes of elements by categories of effects is uniform.

Calculation of criticality failure modes of elements of mechanical systems and their ranking by degree of criticality is important because it points to the elements and their failure modes in which a criticality is the greatest. Analysis of the causes of critical failure modes of elements can be determined directions of undertaking concrete measures to minimize or completely eliminate the causes of failure, or lower the effects of failure. Thus increases the reliability of critical elements, and thus the reliability, dependability and quality of the entire system. Generally, machine system's level of reliability can be increased by increasing the reliability of constitutive components or by introducing the parallel connections. Due to space limitations in motor vehicles steering systems, it is not possible to introduce parallel connections, so the only possibility to increase the system's reliability is through the increase of each component's reliability.

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