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Metodologija načrtovanja zanesljivosti vozil med zasnovo

A Methodology for the Design of Reliable Vehicles in the Concept Stage

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Pri tako močni svetovni konkurenci je bistveno, da imajo motorna vozila veliko zanesljivost. Eden od načinov za doseganje tega cilja je metodologija načrtovanja zanesljivosti vozil. Stopnja načrtovanja je najbolj pomembna v dobi trajanja motornih vozil. Načrtovanje zanesljivosti v okviru faze načrtovanja je v neposredni povezavi z zanesljivostjo motornega vozila. Problem praktične metodologije za načrtovanje zanesljivosti motornih vozil je bil rešen z razvojem postopkov za ta namen. Osnova razvite metodologije predstavlja sodoben pristop k načrtovanju, ki zajema faze zasnove, predhodnega in glavnega načrtovanja z uporabo metode za načrtovanja zanesljivosti v teh fazah. Zaradi razpoložljivega prostora ta prispevek daje poudarek fazam zasnove načrtovanja zanesljivosti vozil.

(Ključne besede: motorna vozila, zanesljivost vozil, načrtovanje zanesljivosti, numerično simuliranje)

With world-wide competition so strong it is essential that motor vehicles have good reliability. One of the ways to reach this goal is the methodology for the design of reliable motor vehicles. The design stage is the most important in the life cycle of the motor vehicle. Reliability design, within the design stage, directly correlates with the reliability of the motor vehicle. The problem of the practical methodology for the reliability design of a motor vehicle was solved by developing a methodology for this purpose. The developed methodology represents a modern approach to design that comprises the phases of conceptual, preliminary and main design with the application of the method for reliability design within these phases. Due to the available space, this paper pays attention to the phase of the conceptual design of the vehicle's reliability.

(Keywords: vehicles, reliability, reliability design, numerical simulations)

0 INTRODUCTION

Reliability is a feature incorporated into a vehicle in the course of the design process, which is realised in the course of production by a high degree of technological discipline, and maintained in the exploitation by continual and stipulated maintenance and orderly usage. In designing reliability, it is necessary to predict or estimate the reliability of each motor-vehicle system element, as far as this is technically possible. The reliability is mainly determined on the basis of the ability of the given part or assembly or system to withstand the unforeseen overloading without catastrophic failure. The reliability of the vehicle elements (system, sub-system, assemblies, sub-assemblies, parts), especially of those critical in terms of reliability, is increasingly becoming the subject of special attention by vehicle designers and the automotive industry in general.

The activities within the design process for motor vehicles and their components are often the result of quite opposing requirements, for example, low vehicle mass combined with high payload, high reliability and safety combined with maximum material savings, and small outline combined with maximum passenger comfort. It is the vehicle designer who has the special responsibility to assess the effect of the technology he or she is converting, by way of his or her efforts and knowledge, into a complex product in accordance with numerous legal regulations. Covering the reliability requirements is inevitable, particularly when designing the motor vehicle's critical parts and assemblies. Providing the designed life with the requested reliability and safety, taking into consideration the appropriate legal regulations, is one of the requirements that have to be fulfilled with modern motor vehicles. Since reliability and long life are the primary goals in motor vehicles design, this means that developing and applying reliability design methods and techniques represents a significant activity in the vehicle-design process ([2], [3], [8], [9], [14], [15], [17] and [18]).

In the field of reliability, reliability-design methods and techniques have been developed to be applied in the phase of system design. However, these methods have been developed on different bases, so it is now difficult to determine which one is the most suitable for application in motor-vehicle design. Perceiving this problem, as well as the problem of comprehensive vehicle design, it has been concluded that it is possible to bind these methods into a single whole, with certain improvements, within the methodology of vehicle-reliability design. In this respect, vehicle-reliability design methodology has been developed ([20] and [21]), and the basis of the modern approach to technical system design, with its phases of concept, preliminary and detail design, are presented in Figure 1. Due to the available space, this paper pays attention to the phase of conceptual design of the vehicle's reliability.

1 RELIABILITY DESIGN

Incorporating reliability requirements and building them into the structure, by applying reliability-design methods and techniques, defines the vehicle's behaviour in terms of failure, and that is the vehicle designer's obligation and responsibility. The basic aim of vehicle-reliability design, i.e., of its elements, is reflected in decreasing the failure-event probability and possible human and material losses. Reliability design has a key role in motor-vehicle development, since reliability analyses and parameters are the entry data for analysing and realising the other design tasks, for the purpose of providing high vehicle effectiveness and efficiency. Maintaining the competing ability implies resolving numerous problems and issues of vehicle reliability and safety for the producer.

The aims of motor-vehicle design are often opposed to the specific dependability requirements, i.e., to the requirements related to reliability, availability and maintainability. This is the reason for investing great efforts and considerable means to meet these requirements. Integrating the overall design goals with the reliability requirements is conducted and mainly executed in the beginning of the initial design phases by establishing an appropriate reliability programme. The framework of the motor-vehicle reliability programme should be closely related to applying and mastering new technologies, as well as to possible difficulties in the design process. In other words, it ought to ensure the data and procedures for solving of these difficulties. In order to have an effective programme for providing vehicle reliability, it has to be planned and process-determined, i.e., with determined assignments, activities for completing them, and methods and techniques for the efficient execution of the activities. The basic tasks of a motor-vehicle reliability-enabling programme are as follows:

- determining the reliability requirements,
- realisation of the reliability-design process,
- supervision and control of the required reliability.

Vehicle users' sensitivity to failures is increasing. It is very often of decisive importance when deciding to purchase a particular vehicle. From the motor-vehicle user's point of view, the most important issue is the one related to the vehicle functioning without failure, i.e., it is related to the length of operating time, during which planned and indicated maintenance is provided. Failure data are the starting point for the quantitative analyses of the reliability, maintenance and safety of the vehicle elements. Bearing in mind the fact that the failure of a vehicle part or assembly is the basic concept for any reliability analysis, vehicle designers have to pay attention to the following:

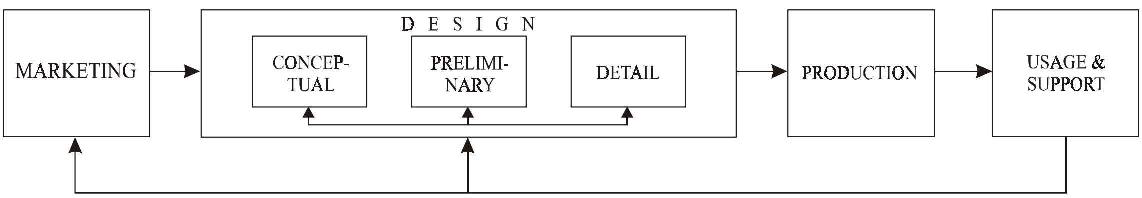


Fig. 1.

- decreasing and minimising the number of failures during operation,
- providing necessary and sufficient warning before a failure occurs,
- enabling the vehicle to continue operation at a lower level in the event of a failure,
- decreasing the costs and shortening the time required for the repair or replacement of the failed part.

The approach to motor-vehicle design that poses such and similar questions and finds the balance in a systematic manner between all the design requirements (functionality, reliability, maintenance, and logistic support) is the design approach and philosophy that ought to be accepted and applied, since it contributes to meeting the users' requirements, legal regulations and to raising the quality of vehicle usage, i.e., attaining market competitiveness. The basis of vehicle-reliability design are the methods of reliability design and the experimental databases ([1] to [3], [13] to [16] and [20] to [22]). Reliability design of vehicles and their elements ought to cover the following:

- the selection of parts and materials that have been standardised as much as possible;
- review and evaluation of all the parts and materials, prior to adopting the design documents, covering the operating characteristics, operating and critical stresses, manufacturing allowances and other features of the parts, for the determined and required function;
- applying only those constituent parts/assemblies that are capable of meeting the reliability goals, i.e., of meeting the requirements of the specification for reliability design.

The process of systems-reliability design includes a series of proceedings and working methods that in their essence have the character of predicting certain states that should be achieved within the system development. The design methods are developed and perfected with the objective of discovering the critical states stated in the process of system design, i.e., identifying possible errors, omissions and shortcomings. The decisions and selections based on the state analysis and on the results obtained from applied reliability-design methods, to a large extent contribute to a qualitative, efficient and effective achieving of the process of system design. The numerous difficulties in this kind of work and in the application of reliability-design methods, as well as the inevitable costs, can all be significantly decreased by a systematic approach, good planning, organised preparation and computer support. The initial bases and necessary preconditions for a complete inclusion of the reliability analysis and design into the vehicle-design process are the following:

- organised databases on failures, operating and critical loads and logistical parameters of motor vehicles and their elements;
- a systemised number of reliability-design methods supported by computer programmes;
- defined criteria for the selection of an optimum reliability-design method;
- the prior experience and knowledge of designers and the technological ability of motor-vehicle producers.

In accordance with the above, a reliability-design methodology has been developed covering the phases of conceptual, preliminary and detailed reliability design, so as to enable the designed system to contain certain, previously set reliability indicators. The framework and reliability design approaches are given for each of the phases, containing the sequence of applying the reliability design methods, the reasons and purpose of their application and the manner of evaluating the achieved results. Due to the wide scope of these results, this paper shows the phase of conceptual reliability design, as a portion of the developed vehicle-reliability design methods.

2 THE PHASE OF CONCEPTUAL RELIABILITY DESIGN

Realisation of the process of system reliability design begins with developing a logical model covering all the available levels of the system design. This implies an organised and systematic approach to using design methods and techniques related to reliability, so as to ensure that the system being designed contains certain reliability indicators that have been stipulated in advance. The final reliability-design objective is installing the stipulated reliability into the system structure ([13] to [16], [20] and [21]).

Identifying and defining the essence of the problem and the selection of the most acceptable solution, i.e., determining a set of quantitative and qualitative reliability requirements, represent the basic goals of reliability design within the phase of the conceptual designing. The correct outlining of the problem, i.e., of the questions, and the timely obtaining of the correct answers at the beginning of the reliability-design process is of special importance for the further realisation and for the success of reliability-design process. Therefore, it is necessary to answer the following questions:

- What is the requested, specified level of reliability?
- Why has that level of reliability been requested and specified?
- How do we realise the reliability requirements and their elements?
- What are the reasons for not being able to attain the requested reliability?
- Is the additional reliability improvement necessary?

Reliability design in the concept-design phase is primarily oriented towards defining the reliability specification and selecting the most acceptable solution from the point of view of a reliability-requirements meeting, which means that the reliability of vehicles and their elements is analysed. The process of vehicle designing is started by translating the users' requirements and needs into the specification for designing, i.e., into the design assignment within of the creation of the pre-design. The concept-design phase also defines the design goals from the point of view of meeting of the standards and regulations an of acceptable limit values, such as the following: the maximum torque burdening the transmission, the maximum operating speeds in individual transmission degrees (the tow diagram), the maximum speed and acceleration, the transmission ratio in the main transmission, and the maximum allowed level of noise. Determining the reliability requirements for each requested vehicle function was conducted on the basis of the identified stipulated functions and the desired reliability level for the covered mileage ([20] to [22]).

The biggest challenge for a reliability designer, and thus for the whole motor-vehicle designers' team, is the initial design activities, when it is possible to perform changes and modifications, practically without any significant material investments and loss of time. Therefore, the battle to successfully incorporate the reliability into the vehicle structure is either gained or lost on the issues of the accuracy, the comprehensiveness and the timeliness of the responses to the previously defined questions, as well as on the issue of forming of a precise and complete reliability specification. When aiming at providing a qualitative development of the concept design phase the literature was reviewed and research was conducted in the field of motor-vehicle reliability ([1], [5] to [8], [11] and [12]).

The basis of vehicle-reliability design methodology are the phases of concept, preliminary and detailed design and the following methods: quality function deployment (QFD), reliability specification , reliability block diagrams (RBDs), reliability functions (RFs), reliability prediction and modelling (RPM), reliability allocation methods (RAM), failure mode, effects and criticality analysis (FMECA), fault tree analysis (FTA), stress-strength interference (SSI), reliability qualification testing (RQT) and design review evaluation (DRE).

In defining the reliability requirements at the level of the vehicle-reliability concept solution and pre-design, the first seven methods were incorporated. In this respect, the reliability algorithm was defined in the conceptual phase, as shown in Figure 2.

2.1 The Algorithm of the Reliability Design Conceptual Phase

The designing of a motor vehicle is shown in the form of a flow diagram, describing in a graphic manner the activities and sequences of the characteristic activities and of the activities in the realisation of the design processes with feedbacks. The flow diagram, based on the following of the system procedure, which is also an algorithmic one, provides a complete understanding of the reliability design problem, so that no major portion is overlooked or omitted. The structure of the system-reliability design proceeding of the developed methodology, as stated earlier, is based on three basic phases: the concept, the preliminary and the detailed, while Figure 2 shows the conceptual phase. These phases often overlap and are executed alternately, with a returning to previous phases through a feedback mechanism. The mainstay of the developed reliability-design methodology is establishing the starting basis for the reliability design and to improve the designers' activities, rendering the improved proceedings of operation for a logical process of considering and deciding, using the methods and techniques of reliability design.

The concept reliability design covers the vehicle system level, where by applying the reliability design methods the systems are considered, i.e., options are evaluated and a decision is made regarding the most suitable solution, according to the established criteria devised on the basis of the vehicle reliability-design specification. In the phase of the vehicle-reliability concept design, the established sequence of applying reliability-design methods is based on their accuracy and complexity. Namely, the reliability methods that are relatively simple are applied first, while the attained results have a lower confidence level, i.e., they are of an orientational character. With the small step forward, a complex method (FMECA), with a higher confidence level, was introduced into the designing process, through which the initial results are corrected in an analytical manner, and substantially more accurate reliability parameters are defined ([11], [16] to [18] and [23]).

In the phase of concept reliability design, a reliability block diagram (RBD) is formed on the basis of knowing the vehicle system structure, the system functioning manner, i.e., the effect of system and subsystem failure on the vehicle's operation. Considering the structure of the vehicle and its systems, from the point of view of functioning, and that of the requested functions, defining is enabled of the satisfactory and unsatisfactory vehicle/ system operations, as well as the manner in which to achieve it. The system, which is divided into functional blocks (systems and subsystems), represents the appropriate connections in the reliability block diagram, which is defined on the basis of the goal function and on the functional block failure. These in turn bring about a vehicle/system failure. RBD represents the basis for defining the vehicle-reliability function. Upon defining the RBD and the reliability function, a further design proceeding is realised in accordance with steps 7 to 15.

2.2 The Method of Quality Function Allocation in the Reliability-Design Process

In accordance with the algorithm, and for the purpose of translating users' needs and requirements (step 1, Figure 2) into quantitative and qualitative indicators, the method of quality function deployment (QFD) is applied, i.e., the procedure for identifying all the factors affecting the design requirements with the aim of meeting users' requirements and the necessary methods and responsibilities for their control. Quality function deployment goes beyond the domain of reliability, since among the users' requirements there are also the users' wishes, but this is a useful and systematic way of pointing out the necessary activities of designing and control, aimed at enabling reliability. The quality deployment function is applied for the purpose of translating of users' requirements into product characteristics, and in that way quality deployment is translated into the user-oriented quality function. The final objective is including the user's "voice" into the process of product development and design, in this case vehicle development and design, regardless of whether it is a brand new or a modified product, with the aim of realising users' requirements with respect to quality.

2.3 Reliability Specification

The model that takes into account users' wishes, requests and needs for the purpose of attaining users' satisfaction, interpreted through the "quality houses", enables an equilibrium between the operating characteristics of the requested reliability levels and the maintenance needed, i.e., the degree of availability of a freight vehicle. In the course of the reliability-specification forming, compromises are quite possible and exchanges between reliability parameters and maintenance parameters for the purpose of accomplishing the requested availability degree, with minimising of the construction costs.

The reliability specification represents a starting point for reliability analyses and estimations, i.e., for the reliability design, and it is the constituent part of the documents related to the stipulated vehicle characteristics and performances. Defining the reliability specification of the vehicle, i.e., of its systems, is based on:

- the reliability data available from the manufacturer, distributor and user of the vehicle,
- requirements and needs of the user, as the main sources of information,
- many years of following up of the vehicle in operational conditions ([19] to [21]).

The specification (*steps 2 & 3, Figure 2*) implies defining the reliability level for the designed mileage and estimated number of failures. For instance, it can be adopted that there are no more than 10% of failures at 300,000 km of covered route. That implies that the number of vehicle systems failures will not be greater than 10%. In that respect, the reliability specification of the vehicle, as well as of its elements, where this level of reliability is expected, is as follows:

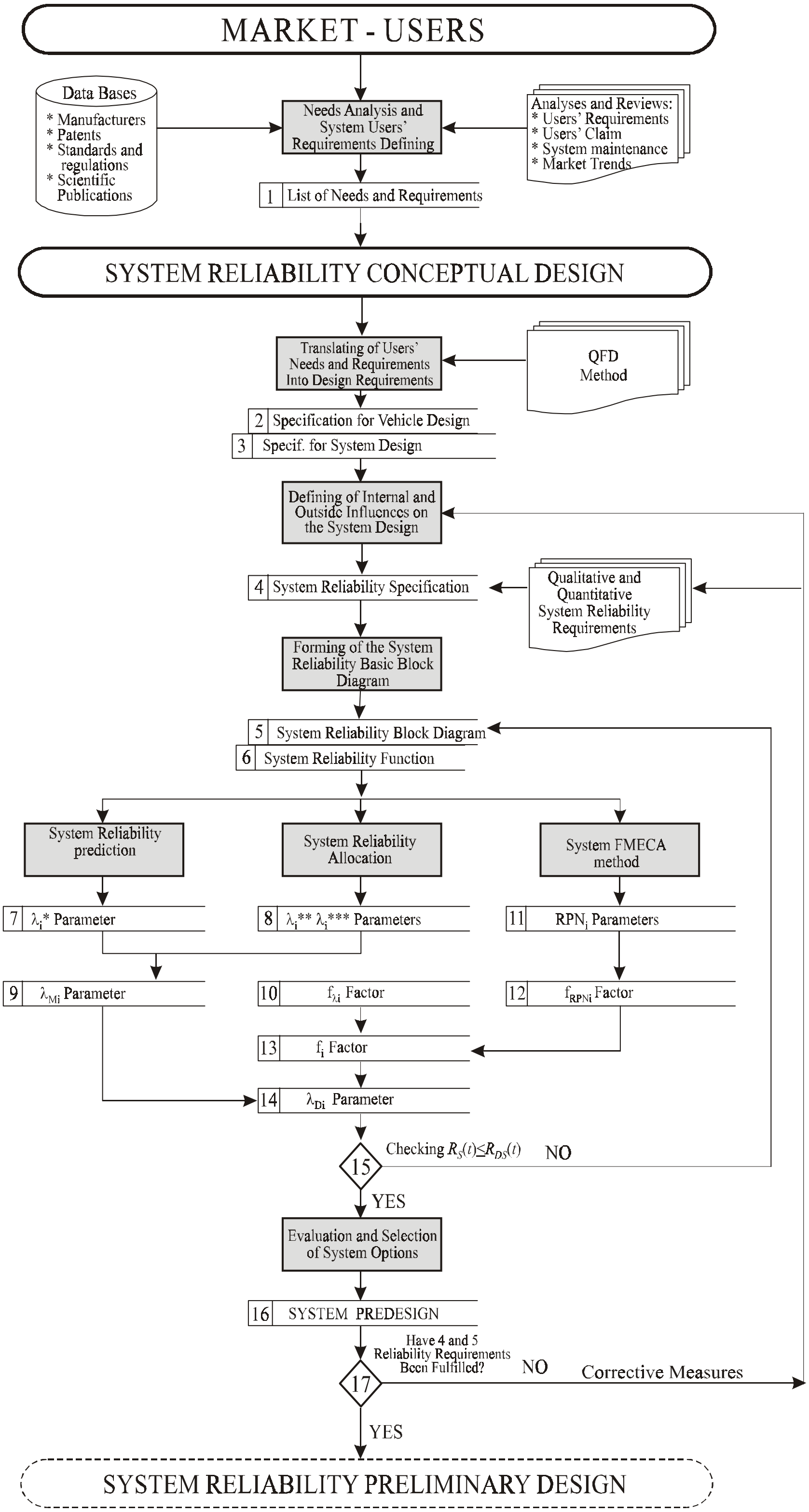

MARKET - USERS
Data Bases
* Manufacturers
* Patents
* Standards and regulations
* Scientific Publications
Needs Analysis and System Users' Requirements Defining
Analyses and Reviews:
* Users' Requirements
* Users' Claim
* System maintenance
* Market Trends
1 List of Needs and Requirements
SYSTEM RELIABILITY CONCEPTUAL DESIGN
Translating of Users' Needs and Requirements Into Design Requirements
QFD Method
2 Specification for Vehicle Design
3 Specif. for System Design
Defining of Internal and Outside Influences on the System Design
4 System Reliability Specification
Qualitative and Quantitative System Reliability Requirements
Forming of the System Reliability Basic Block Diagram
5 System Reliability Block Diagram
6 System Reliability Function
System Reliability prediction
System Reliability Allocation
System FMECA method
7 λi* Parameter
8 λi** λi*** Parameters
11 RPNi Parameters
9 λMi Parameter
10 fλi Factor
12 fRPNi Factor
13 fi Factor
14 λDi Parameter
15
Checking Rs(t)≤RDS(t)
NO
YES
Evaluation and Selection of System Options
16 SYSTEM PREDESIGN
17
Have 4 and 5 Reliability Requirements Been Fulfilled?
NO
Corrective Measures
YES
SYSTEM RELIABILITY PRELIMINARY DESIGN

Fig. 2.

$$VT_{10\%}=300,000\ km \quad (1).$$

On the basis of this condition, the reliability specification (*step 4, Figure 2*) is:

$$R_S(300,000)=0.9 \quad (2).$$

2.4 Reliability Block Diagram

The reliability block diagram *(step 5, Figure 2)* was defined on the basis of the functional-technological connection of the vehicle elements and the analysis of element failures' effect on the vehicle. In other words, the effect of a vehicle system failure upon the vehicle is analysed in the phase of the concept design.

2.5 Reliability Function

On the basis of the defined reliability block diagram and the adopted exponential failure distribution, the reliability function of the vehicle, as well as of its systems, is defined (*step 6, Figure 2*), as follows:

$$R_V(t)=R_S(t)=f_S\left[R_1(t),(R_2(t),.....,R_n(t)\right]= \\ =f_S\left[e^{-\lambda_1 t},e^{-\lambda_2 t},.....,e^{-\lambda_n t}\right] \quad (3)$$

$$R_i(t)=f_i\left[R_{i.1}(t),R_{i.2}(t),.....,R_{i.n}(t)\right]= \\ =f_i\left[e^{-\lambda_{i.1} t},e^{-\lambda_{i.2} t},.....,e^{-\lambda_{i.m} t}\right] \quad (4)$$

where:
- $R_v(t)=R_S(t)$ is the vehicle reliability,
- $R_i(t)$, λ_i reliability, i.e., system failure intensity of the vehicle, i=1- n,
- $R_{i.j}(t)$, $\lambda_{i.j}$ reliability, i.e., subsystem failure intensity of the system, j=1-m.

2.6 Predicting Reliability

On the basis of the available literature and reliability research on vehicles in operation, an estimate is performed, i.e., predicting possible values of failure intensity (*step 7, Figure 2*), i.e., the value is adopted between the following values:

$$\lambda^*_{\min} \langle \lambda^*_{\text{ado}} \langle \lambda^*_{\max} \quad (5)$$

where:
- $\lambda^*_{\min},\lambda^*_{\text{ado}},\lambda^*_{\max}$ are the minimum, the adopted, and the maximum value of failure intensity, respectively.

2.7 Reliability Allocation

In the concept reliability-design phase, the allocation methods are applied (step 8, Fig. 2) of equal distribution λ_i^{**} and λ_i^{***}, in the form:

$$\lambda_i^{**}=\frac{\lambda_S}{n}=\frac{-\ln R_S(t)}{n\cdot t} \quad (6)$$

$$\lambda_i^{***}=\frac{n_i\left[-\ln R_S(t)\right]}{n\cdot E_i\ \cdot t_i} \quad (7)$$

where:
- n, total number of system elements,
- t, the designed time of system operation
- n_i, total number of elements of the i-th subsystem,
- E_i, the subsystem significance degree,
- t_i, time of operation of the i-th subsystem.

The stated failure intensities are applied for determining the λ_{Mi} mean value (step[9, Fig. 2) and $f_{\lambda i}$ failure intensity factor (step 10, Fig. 2), in the form:

$$\lambda_{Mi}=\frac{\lambda_i^*+\lambda_i^{**}+\lambda_i^{***}}{3} \quad (8)$$

$$f_{\lambda i}=\frac{\lambda_{Mi}}{\sum_1^n \lambda_{Mi}}=\frac{\lambda_{Mi}}{\lambda_{DS}} \quad (9)$$

where:
- λ_{Mi}, the failure intensity mean value
- $\lambda_{DS}=\sum_{i=1}^{n}\lambda_{Mi}$, the designed vehicle-failure intensity value,
- $f_{\lambda i}$, the failure intensity factor.

2.8 Failure Mode, Effects and Criticality Analysis – FMECA

Conducting the analysis of the failure mode, the effects and the criticality (FMECA) makes it possible to identify all the potential and known modes of failure occurrences in the system assemblies/parts, their causes, the evaluation of the consequences and the assessment of the failure criticality. Individual system elements (subsystem, assembly, and part) can have several failure modes, since each stipulated function can have several failure modes. Failure modes are allocated, according to the required function, into three groups: complete function loss, partial function loss and wrong function, and this is important for conducting the FMECA method. For each failure mode, the possible effect is analysed at a higher level, i.e., at the whole system level.

By applying the FMECA method, the assessment of the vehicle elements' failure criticality is determined, RPN_i, *(step 11, Fig. 2)* in the form:

$$RPN_i = PF_i \cdot FDV_i \cdot PFR_i \tag{10}$$

where:
- RPN_i, failure criticality degree assessment,
- PF_i, probability of failure occurrence,
- FDV_i, the extent of failure consequence,
- PFR_i, probability of the failure detection.

The assessments of failure criticality RPN_i were applied to determine the failure criticality factor f_{RPNi} *(step 12, Fig. 2),* in the form:

$$f_{RPNi} = \frac{\frac{1}{RPN_i}}{\sum_1^n \frac{1}{RPN_i}} \tag{11}$$

where:
- f_{RPNi}, the failure criticality factor.

2.9 Designed Values of Failure Intensity and Reliability

On the basis of the above-determined values, the factor f_i is determined *(step 13, Fig. 2),* and the designed value of the failure intensity *(step 14, Fig. 2),* in the phase of concept reliability design, is in the form:

$$f_i = \frac{f_{\lambda i} + f_{RPNi}}{2} \tag{12}$$

$$\lambda_{Di} = f_i \lambda_{DS} \tag{13}$$

where in the above expressions:
- f_i, the factor of failure intensity mean value,
- λ_{Di}, the designed failure intensity value.

On the basis of the λ_{Di} design values, the reliability design value is determined in the phase of the concept reliability design, in the form:

$$R_{Di}(t) = e^{-\lambda_{Di} t} \quad (14).$$

According to expressions (3) and (14), the designed vehicle reliability-function value is:

$$R_{DS}(t) = e^{-\lambda_{DS} t} = \prod_{i=1}^{n} R_{Di}(t) = e^{-t\sum_{i=1}^{n} \lambda_{Di}} \quad (15).$$

Using a logarithm, the following is obtained:

$$\lambda_{DS} = \sum_{i=1}^{4} \lambda_{Di} \tag{16}$$

where:
- $R_{Di}(t)$, vehicle system reliability designed value,
- $R_{DS}(t)$, vehicle reliability designed value for the designed time t.

2.10 Checking

Checking *(step 15, Fig. 2)* of the set reliability value $R_S(t)$ and the designed one $R_{DS}(t)$, is done so as to satisfy the condition that:

$$R_S(t) \le R_{DS}(t) \quad (17).$$

In the event of an exponential vehicle failure distribution, as adopted in this paper, the expression (14) is as follows:

$$R_S(t) = e^{-\lambda_S t} = e^{-t\sum_1^n \lambda_i} \le R_{DS}(t) = e^{-t\sum_1^n \lambda_{Di}} = e^{-\lambda_{DS} t} \quad (18).$$

Using the logarithm of expression (18) we obtain:

$$\lambda_S = \sum_1^n \lambda_i \ge \lambda_{DS} = \sum_1^n \lambda_{Di} \quad (19).$$

In the case that the condition given in Equation (18) is satisfied, further designing is continued in accordance with *steps 16 and 17, Fig. 2*, within the phase of preliminary reliability design. Otherwise, in accordance with *step 17, Fig. 2*, it is necessary to take corrective measures according to the given algorithm.

3 EXAMPLE

Due to the wide scope and the complexity of vehicle-reliability designing, this paper gives an example of motor-vehicle systems reliability design, i.e., of the mechanical power transmission system (hereinafter the PTS) of a freight vehicle within the phase of the concept reliability design. However, all that is presented for this particular system can be applied to other freight-vehicle systems as well, and to the vehicle as a whole. Structurally, this system comprises the following: clutch, gearbox, universal joint and rear axle.

The PTS's reliability depends on the reliability of its constituent parts, while the designing and the selection of parts have to be in accordance with the defined stipulated functions of those parts. The stipulated functions are those entered by designing into an item (system, subsystem, or part), jointly comprising its overall operational ability. The quality of the reliability analysis greatly depends on the ability of the designer to identify all the stipulated functions of an item, i.e., to classify the stipulated functions, achieving a definition of the priority. According to the number of constituent subsystems, assemblies and parts, their mutual relations, as well as the great number of stipulated functions, the PTS represents a complex system. Bearing in mind the fact that in the functional sense the PTS is a sequential link, it can be stated that the transmission system reliability design process is a very complex and demanding task that requires a timely establishment of a reliability programme. Taking into consideration the great limitations regarding reducing the number of constituent parts/

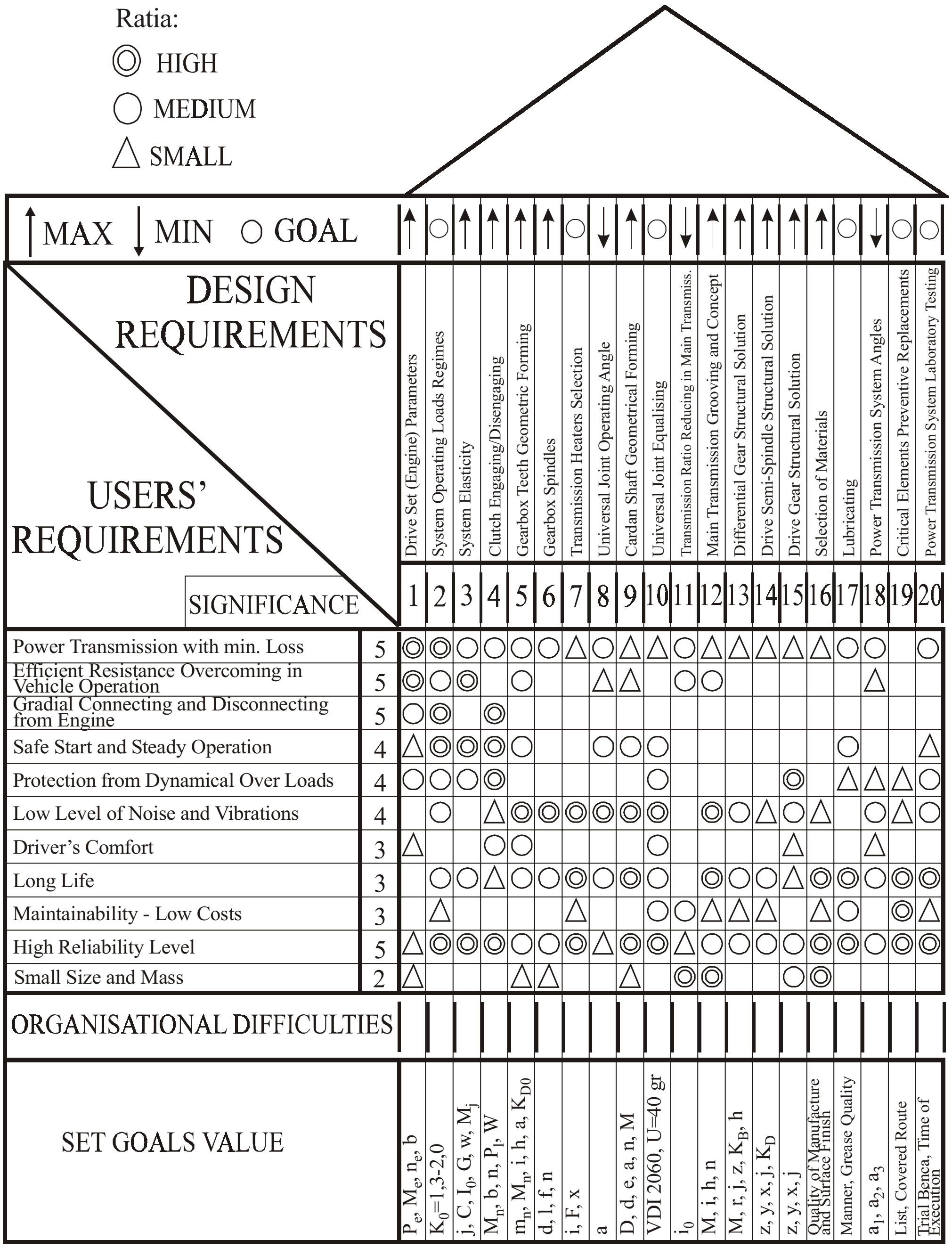


Fig. 3.

assemblies, accomplishing the stipulated system reliability can be obtained by applying reliability design methods and techniques. In accordance with the algorithm in Figure 2, the text below shows the proceeding of reliability design in the phase of concept reliability design for the PTS.

Step 1, Figure 2: Using the QFD method, the vehicle user's needs, requirements and leanings were identified in connection with the PTS, obtained on the basis of processing and analysing the filled-in questionnaires and interviews with a large number of freight-vehicle users. Numerous initial data expressed through the freight-vehicle users' requests and wants, were previously carefully "cleaned" to remove any impreciseness and fuzziness. After that, research of the relevant and measurable system characteristics, i.e., the design stipulations, was conducted, as well as the estimations of interdependence intensities, thus determining the design stipulations that have a major influence on the overall freight-vehicle users' requirements. The design parameters target values were also defined, as well as the guidelines according to which designers can influence the users' requirements. The "quality house" for the PTS, obtained by the QFD method, is shown in Figure 3.

In accordance with steps 2 & 3, Fig. 2, the specification for the PTS of $VT_{10\%}$=300,000 km was adopted, according to what is stated in defining expression (1). In accordance with this value, the stipulated level of PTS reliability was stipulated (*step 4, Fig. 2*), of:

$$R_{PTS} = R_S(300{,}000) = 0.9 \qquad (20)$$

for the designed time t, i.e., for the covered route of 300,000 km.

Step 5, Fig. 2: Based on the analysis of the functional-technological connection of the PTS elements, it was concluded that the PTS fails if there is a failure of the clutch or gearbox, or if there is a failure of the universal joint or drive gear. Therefore, it is a case of independent event failures. On the basis of this, the RBD represents a sequential link of 1-clutch, 2-gearbox, 3-universal joint and 4-drive gear, as shown in Figure 4.b. For example, Figure 4.a. shows the RBD for the vehicle. In defining the RBD for the vehicle, it was accepted that the failure of any system (from S_1, S_2 to S_{PTS} - power transmission system, up to S_n), causes vehicle failure as well.

In accordance with step 6, Fig. 2, and on the basis of the specified reliability, expression (20), the defined RBD, Figure 4.b. and the adopted exponential system-failure distribution, the "mechanical power transmission reliability function" was defined in the form:

$$R_S(t) = \prod_{i=1}^{4} R_i(t) = e^{-\left(\sum_{i=1}^{4}\lambda_i\right)t} = e^{-\lambda_S t} = 0.9 \qquad (21).$$

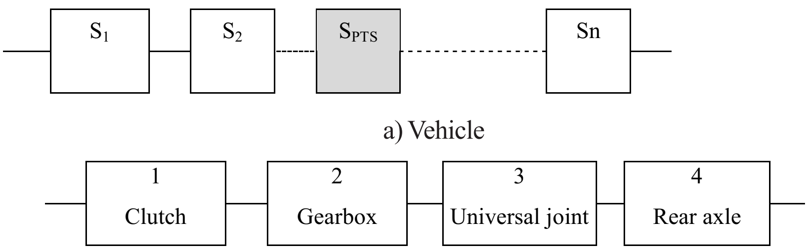
On the basis of this value, for the designed number of kilometres of t = 300,000 km, the failure intensity of the PTS is:

$$\lambda_s = -\frac{\ln R_S(t)}{t} = -\frac{\ln 0.9}{300000} = 0.3512 \cdot 10^{-6}\, km^{-1} \qquad (22)$$

where:

- $R_S(t)$, λ_S, the set value of failure reliability and intensity of PTS,
- $R_i(t)$, λ_i, $R_1(t)$, λ_1, $R_2(t)$, λ_2, $R_3(t)$, λ_3, $R_4(t)$, λ_4, of the failure reliability and the intensity of the subsystem (*i*), i.e., of the clutch, gearbox, universal joint and drive axle, respectively,
- *t=300,000* the freight vehicle designed number of covered kilometres.

After defining the reliability function, and on the basis of the available literature and reliability research performed on vehicles in operation, predicting and allocating failure intensity was performed. In that respect, the failure intensity values of λ_i^* according to Expression (5) *(step 7, Fig. 2)*



b) Power Transmission
Fig. 4.

were adopted and given in Table 1. This table also gives the failure-intensity values allocated by applying the method of equal distribution λ_i^{**} according to expression (6) and λ_i^{***} according to expression (7) (*step 8, Fig. 2*). On the basis of $\lambda_i^{*}, \lambda_i^{**}, \lambda_i^{***}$, the mean values λ_{Mi} were determined, in accordance with expression (8) (*step 9, Fig. 2*), and given in Table 1.

Using the FMECA method, a failure analysis was made and the values were set for the failure criticality degree assessment for the RPN_i according to expression (10) and given in Table 2, *(step 11 Fig. 2)*. On the basis of the RPN_i and expression (11), failure criticality factors were determined and given in Table 1, *(step 12, Fig. 2)*.

According to steps 10 & 13, Fig. 2, i.e., to Expressions (9) & (12), the values of factors $f_{\lambda i}$, i f_i were determined and given in Table 1. On the basis of λ_{Mi}· and these factors, according to Expression (13), the failure-intensity designed values were determined for $\lambda_{Di\,i}$ of the PTS subsystems and given in Table 1.

According to step 15, checking the set values for λ_S and $R_S(t)$, according to Expressions (20) & (22) with respect to the designed values, λ_{DS}, according to Expression (16), Table 1, and $R_{DS}(t)$ according to Expression (15), and consistent with Equations (18) & (19), is a positive one, i.e., we find that:

$$\lambda_S = 0.3512 \cdot 10^{-6} \geq \lambda_{DS} = \sum_{i=1}^{4} \lambda_{Di} = 0.3474 \cdot 10^{-6} \; \left[\mathrm{km}^{-1}\right] \tag{23}$$

Table 1

Subsystem (i)	Failure rate $\lambda \times 10^{-6}[\mathrm{km}^{-1}]$ – Predicting of reliability λ_i^{*}	Allocation reliability – Equal distribution λ_i^{**}	Allocation reliability – AGREE λ_i^{***}	**Mean value** λ_{Mi}	Factor $f_{\lambda i}$	Factor f_{RPNi}	Factor f_i	Failure rate $\lambda \times 10^{-6}[\mathrm{km}^{-1}]$ λ_{Di}
1-Clutch	0.04	0.0878	0.017	0.0483	0.1390	0.0210	0.1745	0.06064
2-Gearbox	0.09	0.0878	0.13	0.1026	0.2952	0.2750	0.2851	0.09907
3-Universal joint	0.05	0.0878	0.034	0.0573	0.1617	0.2050	0.1834	0.06371
4-Rear axle	0.16	0.0878	0.17	0.1392	0.4001	0.3100	0.3550	0.12338
Checking				λ_{MS}= 0.3474	1.0000	1.0000	1.0000	λ_{DS}=0.3474

Table 2

FMECA FORM

RELATED UNIT	COMPONENT	FAILURE – KIND	FAILURE – EFFECT	FAILURE – CAUSE	FAILURE – CONTROL MEASURES	ACTUAL STATUS – PF_i	ACTUAL STATUS – FDV_i	ACTUAL STATUS – PFR_i	ACTUAL STATUS – RPN_i
Power transmission	Clutch	Power flow interruption	Loss of function	Main spring failure	Measuring of rigidity	3	10	8	240
		⋮							
	Gearbox	Power flow interruption	Loss of function	Spindle output failure (stuck, worn out)	Replacement	2	9	10	180
		⋮							
	Universal joint	Power flow interruption	Loss of function	Telescope failure (stuck, worn out)	Testing of operating loads	3	9	9	243
		⋮							
	Rear axle	Power flow interruption	Loss of function	Flat gear failure	Replacement	2	10	8	160
		⋮							

ESTIMATION OF CRITICAL DEGREE BASED ON: Probability of Failure - PF		Failure Demerit Value - FDV		Probability of Failure Remedy - PFR		ESTIMATE OF CRITICAL DEGREE: Risk Priority Number – RPN; RPN = PF x FDV x PFR	
NEGLIGIBLE	1	NEGLIGIBLE	1	CRITICAL	1	Estimated value of RPN	
LOW	2-3	LOW	2-3	HIGH	2-3	LOW	< 50
MEAN	4-6	MEAN	4-6	MEAN	4-6	MEAN	50 -100
HIGH	7-8	HIGH	7-8	LOW	7-8	HIGH	100 - 200
CRITICAL	9-10	CRITICAL	9-10	NEGLIGIBLE	9-10	CRITICAL	>200

$$R_S(t) = e^{-\lambda_S t} = 0.9 \le R_{DS}(t) = \prod_{i=1}^{4} R_{Di}(t) = e^{-t\sum_{i=1}^{4}\lambda_{D,i}} = \quad (24)$$
$$= e^{-\lambda_{DS} t} = e^{-0.3474\cdot 10^{-6}\cdot 300000} = 0.901$$

As the condition given by Equation (18) *(step 15, Fig. 2)* was satisfied, further designing is continued in accordance with steps *16 & 17, Fig. 2*. As the conditions given by Equation (18) were fulfilled, thus simultaneously the conditions given in steps *16 & 17, Fig. 2,* were met. Further designing is continued within the phase of the preliminary reliability design. In this phase, the designing of assemblies, subassemblies and parts is performed, together with the checking of their concord with the values of failure intensities and reliability obtained in operation, by applying of FMECA and FTA methods. In the case that the reliability is to be improved for some of the elements, checking is performed by applying the FTA method, and, if needed, by the methods of stress-strength interference, reliability qualification testing (RQT) and design review evaluation.

4 CONCLUSION

In the modern process of designing vehicles and their elements (systems, subsystems, assemblies, subassemblies and parts), it is necessary to design vehicle reliability as well. For this purpose the methodology of vehicle-reliability design has been developed, with the phases of concept, preliminary and detailed design, based on the developed methods of reliability design.

Upon defining of the users' requirements by applying QFD methods, in the phase of concept design, the vehicle reliability specification is defined, as well as designing the vehicle systems' reliability, with checking of the set requirement for the vehicle-reliability level.

For the purpose of applying the developed methodology, vehicle element failures databases were established, as well as those of the vehicle elements' critical loads. The application of the concept-phase reliability-design methodology has been demonstrated on the example of a mechanical power transmission system. In essence, all that has been presented for this particular system can also be applied to other vehicle systems and elements, and even to the vehicle as a whole.

On the basis of this study it can be concluded that the developed and applied conceptual phase of the methodology enables vehicle-reliability designing at the level of vehicle systems, with the objective of obtaining of a reliable vehicle, which in any case is one of the main prerequisites for competitiveness in the motor-vehicle market.

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