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COMBINED APPLICATION OF FTA AND FMEA METHODS FOR FAILURE ANALYSIS OF TECHNICAL SYSTEMS

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Abstract: *This paper presents the results of research related to the combined application of the Fault Tree Analysis (FTA) and Failure Modes and Effects Analysis (FMEA) methods for analyzing the reliability and safety of technical systems. FTA is a deductive (top-down) method in which, for a defined top event, the causal events that lead to it are identified. FMEA is an inductive (bottom-up) method for conducting reliability and safety analysis from lower to higher system levels. The individual application of these methods is time-consuming and does not provide a complete insight for reliability analysis and risk assessment. The combined application of FTA and FMEA enables the full utilization of the advantages of both methods while minimizing their limitations. Through the sequential application of FTA and FMEA across structural levels and their recursive application from the top to the bottom of the technical system structure, critical components that limit reliable and safe operation can be rapidly identified. The combined application of FTA and FMEA is illustrated through a case study involving the identification of critical components in the control system of light commercial vehicles. The paper concludes with directions for future research in this field.*

Keywords: *failure analysis, FTA, FMEA, combined application.*

1. INTRODUCTION

Reliability analysis of technical systems is based on the failure analysis of their components. Numerous methods have been developed to analyse failures in technical systems and their components. Among these methods, Fault Tree Analysis (FTA) and Failure Modes, Effects, and Criticality Analysis (FMECA) are the most widely used. [1, 2].

Fault Tree Analysis is a deductive analytical method in which, for a predefined top event representing the failure of the considered structural unit or system, the causal events leading to that failure are identified. The basis of Fault Tree Analysis is the representation of physical systems by means of structural logical diagrams.

The FTA method was developed in the early 1960s in the United States for the reliability and safety assessment of military systems [3, 4]. The method was conceived by H. A. Watson of Bell Telephone Laboratories**.** During 1961 and 1962, Watson developed and applied the method to the safety analysis of missile launch systems for the U.S. Air Force. Since the mid-1960s, FTA has been extensively applied to reliability and safety assessment, as well as fault diagnosis, of a wide range of complex technical systems. The method is particularly suitable for analyzing systems whose failures could result in catastrophic effects for human life and the environment.

Failure Modes and Effects Analysis (FMEA) is an inductive method for performing a qualitative analysis of the reliability and safety of a system, proceeding from the lowest to the highest system level [5]. It is based on the examination of all potential failure modes of the system components and their effects on the overall system, with the objective of identifying those failure modes that have the most severe impact on system performance.

FMEA was originally developed for military applications in the United States as a reliability assessment technique for determining the consequences of different failure modes in technical systems. As an official document in the form of a U.S. military standard, the method dates back to November 9, 1949, under the designation MIL-P-1629, entitled Procedures for Performing a Failure Mode, Effects and Criticality Analysis.

The standalone application of Fault Tree Analysis (FTA) and Failure Mode and Effects Analysis (FMEA) methods for risk assessment is time-consuming and does not provide a comprehensive insight into the criticality of system components and their failure modes. Combining these methods leverages their respective strengths while simultaneously minimizing their limitations.

A significant contribution to this field is presented in [6], which proposes a method where FTA and FMEA are applied recursively across different system levels. In this approach, FTA is first utilized to identify potential causes of system failures, after which FMEA is applied to assess the criticality of the identified failures. This procedure is repeated at various levels of the system hierarchy, thereby enabling a detailed analysis of system behavior and a more efficient identification of critical components.

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Further development of integrated methods is presented in [7], which proposes an integrated FTA-FMEA model for risk analysis in complex engineering systems. In this approach, the minimal cut sets identified by FTA are used to determine the importance of individual events within the system. The obtained values are then used to modify the Risk Priority Number (RPN) index within the FMEA, resulting in a more accurate risk assessment and better identification of critical system components.

The combined application of FTA and FMEA methods in this paper is illustrated through a criticality analysis of steering system components in light commercial vehicles. Through the sequential and recursive application of FTA and FMEA methods across the structural levels of the system, the components that restrict safe and reliable operation were determined.

2. FAULT TREE ANALYSIS

An analysis of relevant FTA standards and the literature presented in [4] resulted in the following FTA methodology:
1. Define the system of interest and specify any assumptions to be used in the analysis.
2. Establish the boundaries and objectives of the system,
3. Define the top event of the fault tree. Depending on the analyzed system, it can be general, in the form of a system failure, or a specific case involving only a few failures of the system or its components.
4. Systematically collect and analyze system data (including documentation, calculations, catalogues, service instructions, user complaints etc.).
5. Verify and refine the fault tree. If the fault tree does not accurately reflect the actual system, if all significant events are not included, or if there is no logical relationship between the basic events and the top event, collect additional system data and revise the fault tree accordingly.
6. Perform a qualitative and/or quantitative analysis. Depending on the objective of the analysis, perform a qualitative and/or quantitative evaluation once the fault tree has been verified. For quantitative fault tree analysis, determine the minimal cut sets, which form the basis for most quantitative analyses.
7. Determine appropriate corrective measures. Based on obtained and adopted results through the fault tree, one should provide suggestions for corrective measures aimed at eliminating the perceived defects or proposals for alternative solutions.
8. Whenever the project changes, update and verify the fault tree and the associated analysis.
9. Document the analysis process and follow up on the implementation of identified corrective actions.

In the following basic approach, the development tree, analysis and eventual recommendations for corrective actions are presented as separate steps. In actual practice, there is a great deal of interactions between the steps listed. As a result, the fault tree that evolves includes additions and/or changes reflecting an improved understanding of the various faults.

A fault tree is constructed using event symbols, logic gates, and transfer symbols [5]. A variety of event symbols are employed to distinguish between intermediate (developed) events and basic initiating events. Intermediate events are represented by rectangles. Among the symbols used for basic events, the most common are the circle, representing a component state determined by its inherent characteristics, and the diamond, representing an undeveloped event. The logic gate symbols in a fault tree define the logical relationships and dependencies between events at different hierarchical levels. For example, an OR gate produces an output if one or more input events occur, whereas an AND gate produces an output only if all input events occur. Transfer symbols facilitate the construction of complex fault trees by linking the main fault tree to one or more subtrees.

3. FAILURE MODES AND EFFECTS ANALYSIS

FMEA is fundamentally a procedure for the qualitative assessment of the reliability of technical systems. A logical extension of FMEA is the quantification of failure-related parameters of system components and the evaluation of their criticality. This extension, which focuses on assessing the degree of criticality of individual components with respect to the system or its mission, is referred to as Criticality Analysis (CA). Criticality is generally defined as a relative measure that combines the severity of the consequences of a failure mode with its frequency of occurrence. Combining FMEA and CA results in Failure Modes, Effects, and Criticality Analysis (FMECA).

FMECA can be applied at various stages of a product life cycle. According to the literature, it is most commonly used to analyze technical system components during the product development phase and to evaluate operational data collected during product service.

When failure data for the components of a technical system are available from operational experience, or when the relevant failure indicators can be reliably estimated, the quantitative FMECA procedure is performed in three steps [1, 8]:
1. Determination of criticality of failure mode j of component i is to be done by categories of failure effects k (k = 1, 2, 3, 4), using:

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

where α_{ij} is a relative portion (frequency measure) of failure mode j of component i ($0 \le \alpha_{ij} \le 1$, $\sum_j \alpha_{ij} = 1$); $\beta_{ij}^{(k)}$ is conditional probability that failure mode j of component i will cause category k failure effect according to the adopted classification (values are taken from Table 1; $\lambda_i = \sum_j \lambda_{ij}$ is failure rate of component i; λ_{ij} is part failure rate of mode j of component i, and t_i is operating time of component i.

Table 1. Values of conditional probabilities

Degree of occurrence of the *k*-th failure effect category	$\beta_{ij}^{(k)}$ [-]
Certain event	1
Probable event	0.1 ... 1
Most probably would not happen	0 ... 0.1
Practically doesn't happen	0

Calculated values of $C_{ij}^{(k)}$ are the initial basis for determination of other quantitative properties of component criticality. They make it possible to rank the component failure modes according to effects in order to evaluate the most critical system failure modes from the aspect of safety.

2. Determination of failure criticality of component *i*, which causes the *k*-th category of failure effects:

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

Calculation of $C_i^{(k)}$ enables the identification of the most critical components whose failures lead to specific categories of effects.

3. Criticality of the *k*-th system effect category, determined by summing the criticalities of all component failure modes for the specified effect category:

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

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

For quantitative FMECA of technical systems, a computer program was developed as part of this study.

This software consists of a routine for calculation of failure modes criticality and effect categories and their ranking, a subroutine for transformation of components of arbitrary array into descending series and a routine for forming of input files.

4. COMBINED APPLICATION OF FTA AND FMEA METHODS

The standalone application of FTA and FMEA methods has certain limitations.

The way the top event in the fault tree is defined greatly influences the success of the analysis. If the event is too general, the analysis becomes cumbersome and unmanageable. Conversely, if the event is too specific, the analysis does not provide sufficient insight into the system. Constructing a fault tree for complex technical systems is time-consuming, leading to delayed results during the product development phase. The focus of fault tree analysis is placed on analyzing the root causes of failures that lead to system failure. The consequences of failures on the potential system breakdown, people, and the environment are not considered. In addition, the FTA method has limited capabilities regarding component criticality analysis.

FMEA focuses on the analysis of individual components and often neglects complex interdependencies between various events within the system. FMEA is not suitable for application in complex technical systems.

Consequently, numerous researchers have proposed integrated approaches that combine FTA and FMEA to leverage the advantages of both methods and mitigate their individual limitations.

The combined FTA and FMEA method utilizes deductive and inductive approaches as needed. The constructed fault tree for the adopted top event, the constituent components, and their functions are considered in parallel. The objective of the method is to perform a comprehensive analysis of the causes, modes, and consequences of component failures based on the constructed fault tree and the completed FMEA worksheet. The fault tree enables a complete analysis of cause-and-effect relationships between events. Procedures defined within the FMEA method are used to analyze the criticality of component failure modes. It should be emphasized that these procedures significantly differ between FMEA based on product operational data and FMEA in the development phase. In the product development phase FMEA, the following parameters are determined for each identified component failure mode: Severity, Occurrence, and Detection. Based on these parameters, the Risk Priority Number (RPN) is calculated using the formula:

$$\text{RPN} = \text{Severity} \times \text{Occurrence} \times \text{Detection} \tag{4}$$

The obtained RPN values are used to rank the identified component failure modes and to prioritize the implementation of corrective actions.

The results of the quantitative fault tree analysis, in the form of minimal cut sets of events, enable the correction of RPN values and an improved risk assessment.

The combined method is particularly suitable for analyzing component failures in complex technical systems. It enables the precise identification of critical components. The proposed integrated approach allows for a more efficient system reliability analysis by combining the benefits of both approaches.

The columns of the FMEA worksheet regarding failure modes, causes, and consequences of component failures are filled out based on the constructed fault tree. This implies that the results of the FTA method are used as an input for the FMEA analysis, representing a sequential approach. To reduce the time required to obtain results on the criticality of complex technical system components and to decrease analysis complexity, it is expedient to conduct the described analysis procedure recursively across the structural levels of the system.

In the combined application of FTA and FMEA methods, the synergistic effect is fully realized. Namely, the contribution of the integrated application of FTA and FMEA in terms of work efficiency and effectiveness, as well as minimizing the time required to achieve the desired results, is significantly greater than the sum of the results of their individual applications.

5. CRITICALITY ANALYSIS OF STEERING SYSTEM COMPONENTS USING THE COMBINED FTA AND FMEA METHODS

5.1. Criticality analysis of system components

As part of the master's thesis [9], the research findings of which were published in [10, 11, 12, 13], the failures of the steering system of light commercial vehicles were analyzed using the FTA and FMEA methods. By constructing the fault tree, a cause-and-effect relationship was established between system failures and the failures of components at the lowest structural level. This approach made it possible not only to identify the most common failure modes of the system components but also to determine their ultimate effects.

With the objective of identifying the critical components that limit the reliable and safe operation of the steering system, a quantitative FMECA of the steering system components of commercial vehicles was performed using operational data. This analysis was based on a comprehensive dataset, part of which is presented in Table 2. The third column of Table 2, listing the failure modes of the system components, was derived from the fault tree. Furthermore, the effect categories assigned to the individual component failure modes (Column 7) were determined based on the intermediate events identified in the fault tree. The procedure used to collect the remaining data presented in Table 2 is described in detail in the cited references.

Table 2. Excerpt from the data table for the quantitative FMECA of the steering system of light commercial vehicles

Component name	Q [-]	Failure mode	Failure mode code	Rel. rate α_{ij} [-]	Loss prob. β_{ij} [-]	Final effect	t_{srj} [km] x10^3	t_{sri} [km] x10^3
Steering wheel 61001	1	Damage Insufficient tightening of screws	N.06 N.31	0.02 0.01	1.0 0.1	*k*.4 *k*.2	20 3	873.4
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	130
Rubber insert 61011	1	Cracking	N.06	1	1.0	*k*.3	200	200
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	895.4
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	99.9
Tie-rod ball joint 62210	1 1 1	Body joint deformation Fracture of the eyeball or the ball joint 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	99.9

By processing the data presented in Table 2, using the software program for conducting quantitative FMECA, the following results were obtained:

- degree of criticality of the failure modes of the steering system components, regardless of their effects,
- degree of criticality of the steering system components according to the effects of their failure modes, and
- degree of criticality of the final effects of failures of the steering system components.

Based on the degree of criticality of the final effects of failures in the steering system components, 99.38% of the components are associated with failure modes classified within the third effect severity category (the input and output parameters of the steering system exceed the permissible limits; examples of such deviations include increased backlash, steering wheel torque requirements that exceed normal operating values and misaligned wheel geometry resulting from the deformation of steering linkage components). Table 3 presents an excerpt from the criticality ranking of the steering system components according to failure effects, specifically referring to the components assigned to the third effect severity category.

Table 3. Degree of component criticality by effects on *k*.3

No.	Code	Component name	Criticality
1	62210	Tie-rod ball joint	0.5995E-03
2	62110	Lever with ball joint	0.5995E-03
3	61005	Steering shaft bushing	0.4608E-03
4	61011	Rubber insert	0.3003E-03
5	61110	Shaft with segment	0.3986E-05
6	61002	Steering shaft	0.8208E-06
7	61107	Slide bearing of output shaft	0.6707E-06
8	61104	Roller bearing of the steering head	0.5429E-06
9	61012	Flange on the worm shaft	0.4567E-06
10	61103	Worm shaft	0.4558E-06
11	61004	Steering shaft bracket	0.4027E-06

Figure 1 shows Pareto analysis of criticality of the steering system components with failure modes that have a third category of effects.

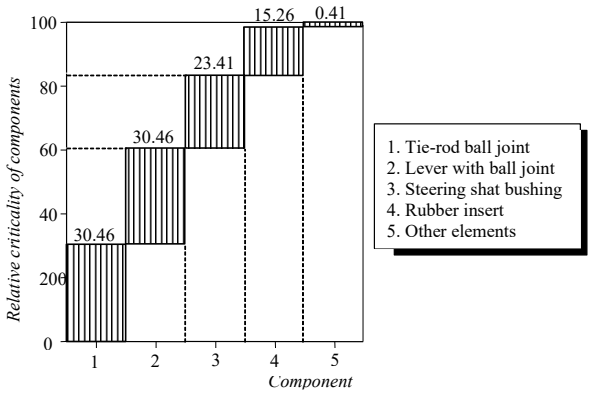


Figure 1. Pareto analysis of criticallity rate of components for category of effects *k*.3

Based on the results of the program for a quantitative analysis of the degree of criticality and Figure 1, it can be concluded that the most critical components of steering system in terms of durability and safety are: tie-rod ball joint, the lever of the longitudinal tie-rod with ball joint, steering shaft bushing and rubber insert of coupling. All other components are within 0.41% of criticality.

5.2. Criticality analysis of the tie-rod ball joint

Based on the previous analysis, it was determined that the tie-rod ball joint and the lever with the ball joint are the most critical components of the steering system. It should be emphasized that the criticality of the lever with the joint is conditioned by the criticality of the joint. In the further study, by applying a combined FTA and FMECA method, the criticality of failure modes and parts of the tie-rod ball joint was determined [9, 13]. To identify potential failure modes of the tie-rod ball joint, a fault tree was formed, shown in Figure 3. In this way, potential failure modes were recorded and their effects determined. The results of the FTA analysis were used to complete Table 4 with data for quantitative FMECA of the tie-rod ball joint parts.

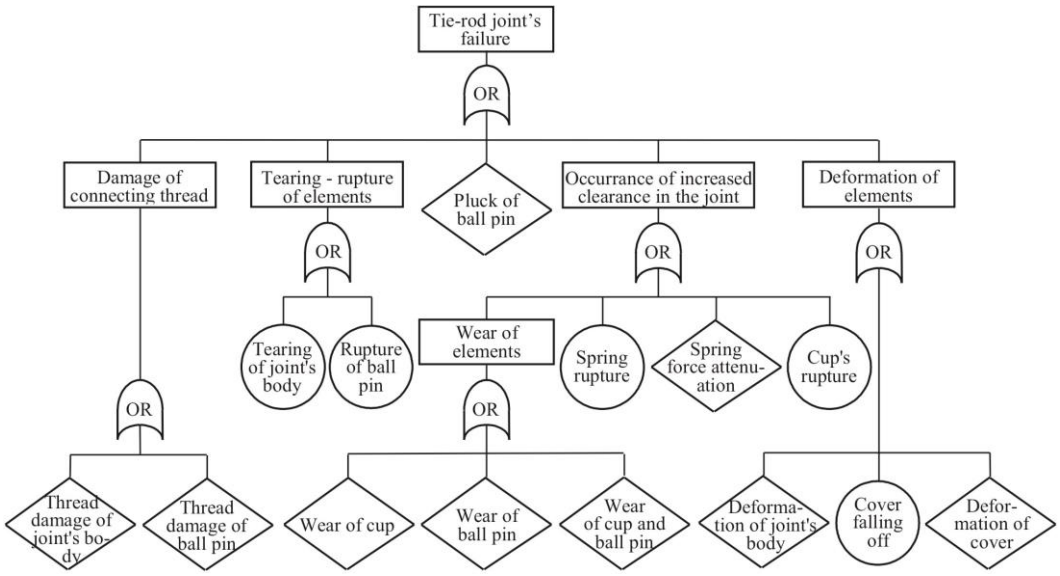


Figure 2. Independent failure tree of the light commercial vehicle steering tie-rod ball joint

Table 4. Basics of the FMECA procedure for components of the tie-rod ball joint for light trucks

Component name	Q [-]	Failure mode	Failure mode code	Rel. rate α_{ij} [-]	Loss prob. β_{ij} [-]	Final conseq.	t_{srj} [km] x10^3	t_{sri} [km] x10^3
Joint body 62211	1	Deformation Tearing of joint body Thread damage	N.02 N.06 N.07	0.0001 0.0007 0.003	0.3 1.0 0.8	*k*.3 *k*.1 *k*.2	200 200 100	≈100
Ball pin 62212	1	Rupture (tearing)of ball pin Thread damage Pluck of ball pin Wear	N.06 N.07 N.29 N.77	0,0007 0.0030 0.0002 0.9961	1.0 0.9 1.0 1.0	*k*.1 *k*.2 *k*.1 *k*.3	200 100 100 100	≈100
Cup 62213	1	Cup rupture Wear	N.06 N.77	0.003 0.997	0.7 1.0	*k*.3 *k*.3	150 100	≈100
Spring 62214	1	Spring rupture Spring force attenuation	N.06 N.12	0.0008 0.001	1.0 0.8	*k*.3 *k*.3	200 20	100
Cover 62215	1	Deformation Cover falling off	N.02 N.29	0.0002 0.0004	0.7 1.0	*k*.3 *k*.3	100 200	≈100
Sealing cap 62216	1	Total rupture Falling off Appearance of small rifts	N.06 N.29 N.37	0.002 0.007 0.004	1.0 0.9 0.2	*k*.4 *k*.4 *k*.4	30 150 20	99.89

By processing the data presented in Table 4 using the software program for conducting quantitative FMECA, the following results were obtained:

- degree of criticality of the tie-rod ball joint components failure modes, regardless of their effects,
- degree of criticality of the tie-rod ball joint components according to the effects of their failure modes, and
- degree of criticality of the final effects of failures of the tie-rod ball joint components.

Based on the degree of criticality of the ultimate failure effects of the tie-rod ball joint component, 99.21% of the total criticality sum of the components refers to failure modes of components with the third category of effects. Table 5 presents the ranked criticality values of parts for effect category *k*3.

Table 5. Degree of component criticality by effects on *k*.3

No.	Code	Component name	Criticality
1	62213	Cup	0.5986E-03
2	62212	Ball pin	0.5965E-03
3	62214	Spring	0.9598E-06
4	62215	Cover	0.3239E-06
5	62211	Joint body	0.1796E-07

Figure 3 shows distribution of criticality degree of the tie-rod components for effect category *k*.3. As it may be seen in Figure 3, failure of the tie-rod ball joint in the largest number of cases appears due to failure of the cup or the ball pin, while only 0.11% is due to other components.

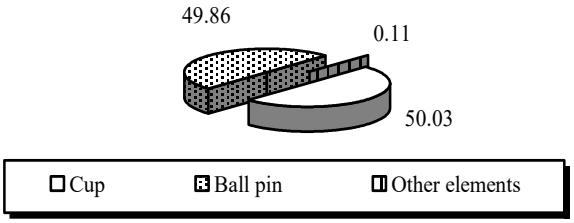


Figure 3. Distribution of degree of criticality for components of the steering system tie-rod ball joint for category of effects *k*.3

Analysis of the causes of failures in steering system tie-rod ball joint components can help identify appropriate measures to minimize or eliminate the causes of failures, or to reduce their effects.

6. CONCLUSION

The research results show that the integrated application of FTA and FMEA methods represents an effective approach for reliability analysis and risk management in complex technical systems. The combination of FTA and FMEA enables the identification of critical system components as well as more precise risk ranking based on the system structure and the characteristics of individual failures. The proposed methodology can be applied in various industrial fields, including manufacturing systems, electronic devices, and complex technical systems. As a direction for future research, the integration of this methodology with other risk analysis methods, such as probabilistic models, fuzzy logic, and Bayesian networks, is proposed to enable even more accurate quantitative risk assessment in complex technical systems.

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References

[1] DHILLON,B.S.: *Design reliability, fundamentals and applications*, Department of Mechanical Engineering, University of Ottawa, Ottawa, Ontario, Canada, CRC Press LLC, 1999.

[2] BERTSCHE,B.: *Reliability in automotive and mechanical engineering.* VDI-Buch, Springer-Verlag, Berlin Heidelberg, 2008.

[3] ERICSON,C: *Fault Tree Analysis – A History*, in: *Proceeding of the 17th International System Safety Conference*, 1999, http://www.fault-tree.net/ papers /ericson-fta-history.pdf. Accessed: 17. 01. 2010.

[4] CATIC,D., M. GASIC,M., SAVKOVIC,M., GLISOVIC,J.: *Fault tree analysis of hydraulic power-steering system*, International Journal of Vehicle Design, Inderscience Publishers, United Kingdom, Vol. 64, No 1, pp. 26-45, 2014.

[5] STAMATIS,D.H.: *Failure mode and effect analysis*, 2nd ed., American Society for Quality, Milwaukee, Wisconsin, 2003.

[6] PEETERS,J.F.W., BASTEN,R.J.I., TINGA,T.: *Improving failure analysis efficiency by combining FTA and FMEA in a recursive manner,* Reliability Engineering & System Safety, DOI: 10.1016/j.ress. 2017.11.024

[7] SHAFIEE,M., ENJEMA,E., KOLIOS,A.: *An integrated FTA-FMEA model for risk analysis of engineering systems*, Journal: Applied Sciences, DOI: 10.3390/app9061192, 2019.

[8] Military standard MIL-STD-1629A (1980). *Procedures for Performing a Failure Mode, Effects and Criticality Analysis* Department of Defense, Washington.

[9] ĆATIĆ,D.: *Development of accelerated experimental testing procedures for reliability assessment of systems in mechanical engineering*, Master'ş thesis, Faculty of mechanical engineering in Kragujevac, 1995.

[10] ĆATIĆ,D.: *Fault tree analysis of the causes of steering system failures in light commercial vehicles*, Statistical methods and quality system certification, OMO, Belgrade., (1994)., pp. 131-142.

[11] ĆATIĆ,D., JOVIČIĆ,S.: *Analysis of failures of the light industrial vehicle steering system by using the fault tree technique*, MVM - Volume 22, Number 1/2 - Kragujevac, (1996), pp. 14-29.

[12] ĆATIĆ,D., PAPIĆ,LJ.: *Ranking of steering system components in light commercial vehicles according to their criticality level*, Statistical methods and quality system certification, OMO, Belgrade., (1994), pp. 115-130.

[13] ĆATIĆ,D.: *Development and application of reliability theory methods*, Monograph, Faculty of mechanical engineering, Kragujevac, 2005.