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SENSITIVITY ANALYSIS OF VEHICLE SYSTEM'S RELIABILITY BLOCK DIAGRAM WITH HIERARCHICAL APPROACH

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ABSTRACT

Often denoting 'dependability' reliability – that–, has taken on a broad meaning in daily life. Reliability is defined as a vehicle system's capability to perform its required function. Reliability analysis methods are defined by the international standard IEC 60300-3-1. One of the most widely used quantitative analyses is the Reliability Block Diagram (RBD) method. The theoretical and practical investigation of canonical systems and their reliability has become important in several fields of vehicle engineering. This raises crucial questions regarding the sensitivity of reliability of the investigated vehicle system. The main aim of this paper is to show the implementation of mathematical diagnostic methodology of aircraft systems and gas turbine engines in order to determine the sensitivity of reliability of a canonical vehicle system. The proposed method is called Hierarchical Sensitivity Model of Reliability Block Diagram (HSMoRBD). This work demonstrates the theory of the proposed method and hows its applicability by way of an example.

Keywords: reliability; Reliability Block Diagram; sensitivity; interconnection

1. INTRODUCTION

In today's competitive world, the reliability of equipment is vital to maintain quality [6]. Reliability analysis methods are defined by the international standard IEC 60300-3-1. The most widely used quantitative analyses are Fault Tree Analysis (FTA) and Analysis of Reliability Block Diagram (RBD) [2].

The scientific work of the author is part of the project "Dynamics and Control of Autonomous Vehicles meeting the Synergy Demands of Automated Transport Systems" (EFOP-3.6.2-16-2017-00016), with the participation of the following research consortium: Széchenyi István University, John von Neumann University, University of Dunaújváros and Óbuda University. In the course of this project Nagy and Tuloki explored a real sensor and commutation network system of a fully electric vehicle (Nissan Leaf Z0) and depicted its block diagram [3].

In the literature on reliability engineering, there are many studies books as well as papers dealing with reliability theory from both theoretical and practical point of view.

Boucerredj proposed a dependability evaluation of a system controlled by computer using a new approach is based on optimization qualitative and quantitative analysis [1]. This qualitative analysis optimization based on the Truth Table method combined with the Karnaugh Table used for focusing on the identifying failure on the system study (or parts of the system). This is relevant for dependability analysis, where the objective is to de-termine the causality events between nominal states, degraded state and feared state for de-riving Minimal Feared State (MFS).

The papers of Wang et al. discussed the application and accuracy of different analysis techniques supporting the determination of industrial and commercial power system reliability and availability. Simulation via RBD is a practical and applicable technique in the determination of industrial and commercial powers system reliability and availability [9].

Szakács introduced a model of a pneumobil vehicle developed at the Óbuda University [7]. The goal of that modelling was to describe the air pressure and flow, force, and speed behavior of the piston, in order to optimize drive power, and gas consumption. Further goals included the development of a functional block model of pneumobil's driving system for optimizing its control strategies, with special focus - on maximizing vehicle power, and traveling range [8].

Pokorádi developed modular approached sensitivity models called Linear Sensitivity Model of System Reliability (LSMoSR) and Linear Sensitivity Model of System Unreliability (LSMoSU) [5].

The present article follows in the spirit of these works and proposes a new Hierarchical Sensitivity Model of Reliability Block Diagram (HSMoRBD).

The paper is organized as follows; Section 2 represents the Reliability Block Diagram method theoretically and in practice. Section 3 explains the methodology of hierarchical sensitivity analysis of RBD firstly theoretically and then by a case study. Section 4 contains the discussion, while Section 5 summarizes the paper and proposes some future research directions.

2. RELIABILITY BLOCK DIAGRAM

The Reliability Block Diagram is easy both to evaluate and to understand. It has been widely used in reli-ability engineering for many years Its general methodology is depicted by the international standard IEC 60300-3-1 [3]. The method provides a perclear graphical representation of the redundancy inherent in the investigated system.

The RBD can only be used for reliability investigation of simple systems. A simple system does not have so-called complex interconnections, therefore it can be represented as a network in which the components and subsystems are connected in series, in parallel, or in a combination of these.

The RBD has equivalent mathematical characteristics to the Fault Tree Analysis (FTA).

The serial system means that all of its components must work in order for the system to be successful. Its reliability can be determined by

$$R=\prod_{i=1}^{n} r_i \quad . \tag{1}$$

equation, where:

r_j – reliability of j^{th} element;

n – number of elements.

In case of the parallel system, to ensure success, either one or more elements must operate successfully. So, the reliability of the parallel system is:

$$R=1-\prod_{i=1}^{n}(1-r_i) \quad . \tag{2}$$

It must to be mentioned that from reliability point of view serial or parallel system does not refer to any serial or parallel connections from a technical, technological aspect.

The combined RBDs can be serially-parallel or in parallel-serial combination. Their models include a combination of the redundant and no redundant elements or subsystems. In this case, the different layers of the RBD should be defined.

Fig. 1 shows the RBD of the investigated system. The system layers can be seen in Fig.2.

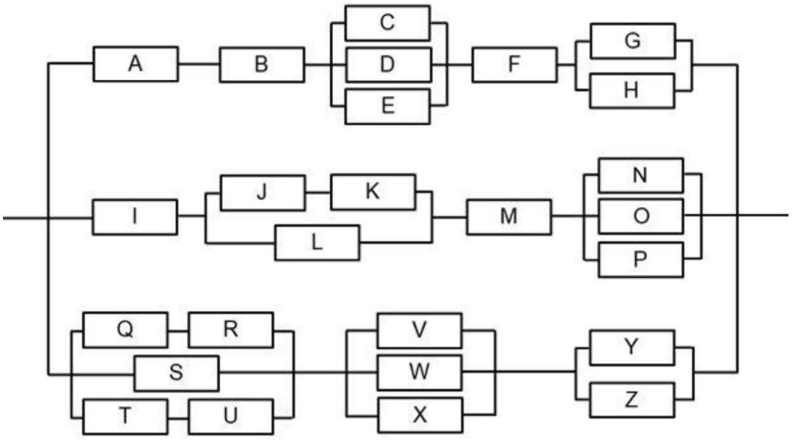

Fig. 1 Block Diagram of the Investigated System

Layer 1:

The investigated system has been modelled as subsystem 1 (upper); 2 (middle) and 3 (undermost) with parallel connections. Therefore, the reliability of system:

$$R_{sys} = 1 - \{(1 - R_1)(1 - R_2)(1 - R_3)\} \ . \tag{3}$$

Layer 2:

The Layer 2 contains the elements or subsystems of three parallel branches connected in series.

Subsystem 1 is composed of elements A; B and F as well as the Subsystems 11 and 12:

$$R_1 = r_A r_B R_{11} r_F R_{12} \ . \tag{4}$$

Subsystem 2 consists of elements I and M and Subsystems 21and 22:

$$R_2 = r_I R_{21} r_M R_{22} \ . \tag{5}$$

Subsystem 3 has Subsystems, namely 31; 32 and 33:

$$R_3 = R_{31} R_{32} R_{33} \ . \tag{6}$$

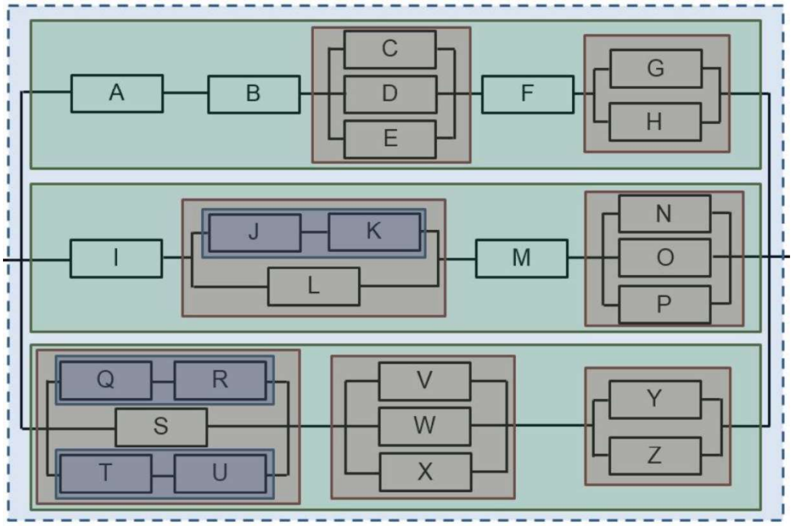

Fig. 2 The Layers of Block Diagram of the Investigated System

Layer 3:

In the Layer 3 there are the components 11 (C;D;E); 12 (G;H); 21 (211; L); 22 (N; O; P); 31 (311;S; 312); 32 (V; W; X) and 33 (Y; Z). These components consist of elements and components connected in series. Their reliabilities should be determined separately:

$$R_{11} = 1-\{(1-r_C)(1-r_D)(1-r_E)\} \ . \tag{7}$$

$$R_{12} = 1-\{(1-r_g)(1-r_H)\} \ . \tag{8}$$

$$R_{21} = 1-\{(1-R_{211})(1-r_L)\} \ . \tag{9}$$

$$R_{22} = 1-\{(1-r_N)(1-r_O)(1-r_P)\} \ . \tag{10}$$

$$R_{31} = 1-\{(1-R_{311})(1-r_S)(1-R_{312})\} \ . \tag{11}$$

$$R_{32} = 1-\{(1-r_V)(1-r_W)(1-r_X)\} \ . \tag{12}$$

$$R_{33} = 1-\{(1-r_Y)(1-r_Z)\} \ . \tag{13}$$

Layer 4:

The reliability of the 211 (J; K); 311 (Q; R) and 312 (T; U) components of the Layer 4:

$$R_{211} = r_J r_K \ . \tag{14}$$

$$R_{311} = r_Q r_R \ . \tag{15}$$

$$R_{312} = r_T r_U \; . \tag{16}$$

Then – using equations (3) – (16) backwards – a

$$\mathbf{y} = f(\mathbf{x}) \; . \tag{17}$$

general vector-vector function can be set up, where:
x – vector of reliabilities of elements;
y – vector of reliabilities of system and subsystems (components).

$$\mathbf{y} = \begin{bmatrix} R_{sys} & R_1 & R_2 & R_3 & R_{11} & R_{12} & R_{21} & R_{22} & R_{31} & R_{32} & R_{33} & R_{211} & R_{311} & R_{312} \end{bmatrix} \tag{18}$$

$$\mathbf{x} = \begin{bmatrix} r_A & r_B & r_C & r_D & r_E & r_F & r_G & r_H & r_I & r_J & r_K & r_L & r_M & r_N & r_O & r_P & r_Q & r_R & r_S & r_T & r_U & r_V & r_W & r_X & r_Y & r_Z \end{bmatrix}$$

Fig. 3 shows the reliabilities of the system and subsystems 3; 31 and 312 in the case of different reliabilities of all components r_i.

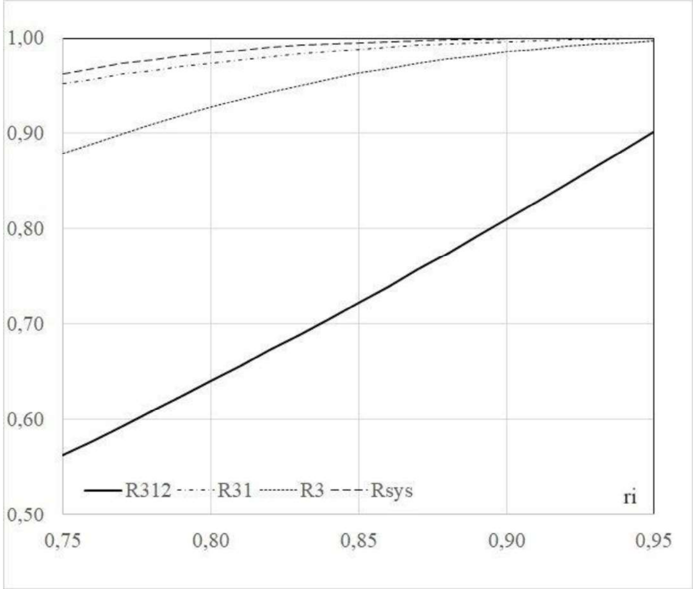

Fig. 3. Reliabilities of the System and Subsystems 3; 31 and 312 depend on Reliabilities of Elements

3. HIERARCHICAL SENSITIVITY ANALYSIS

Generaly, sensitivity analysis shows how sensitive the system's output parameter is while changes in any elements of the input parameters [6]. In other words the sensitivity coefficient characterizes measurement of the investigated output system parameter's dependence upon a given input. This Section focuses on the methodology of the hiereachical approach sensitivity model setting up and will be depicted theoretically and demonstrated practically through the example of the above-mentioned sample RBD.

Using the mathematical model of the investigated system or process relative changing of output parameters can be determined in the case of change in input parameter (or parameters). Acording to the autors of [5] and [6], the sensitivity the input parameter x_i

of the general function $f(x_1;x_2;...x_m)$ can be determined analytically by the coefficient:

$$K_{y,x_i} = \frac{\partial f(x_1;x_2;...x_m)}{\partial x_i} \frac{x_i}{f(x_1;x_2;...x_m)} \quad . \tag{19}$$

Using this coefficient, the

$$\delta y = K_{y1}\delta x_1 + K_{y2}\delta_{x2} + ... + K_{ym}\delta x_m \quad . \tag{20}$$

linear sensitivity equation can be determined, which depicts the relative sensitivities of output (dependent) parameters depending on relative changes of input (independent) parameters.

The sensitivity coefficients of RBD can be determined in the following ways:

In the case of serial systems (or subsystems) – using equation (1):

$$R = \prod_{i=1}^{n} r_i \quad \Rightarrow \quad K_i = 1 \quad . \tag{21}$$

In the case of parallel systems (or subsystems) – using equation (2):

$$R = 1 - \prod_{i=1}^{m}(1 - R_i) \quad \Rightarrow \quad K_i = \frac{R_i}{R_{sys}} \prod_{\substack{j=1 \\ j \neq i}}^{m} (1 - R_j) \quad \cdot \tag{22}$$

Using the sensitivity coefficients determined above and equation (17), the linear sensitivity model of reliability of the investigated system can be formulated on a general level as

$$\mathbf{A}\delta\mathbf{y} = \mathbf{B}\delta\mathbf{x} \quad , \tag{23}$$

$$\mathbf{S} = \mathbf{A}^{-1}\mathbf{B} \quad , \tag{24}$$

$$\delta\mathbf{y} = \mathbf{S}\delta\mathbf{x} \quad , \tag{25}$$

equation, where:

A – coefficient matrix of elements;

B – coefficient matrix of system and subsystems;

S – relative sensitivity coefficient matrix of investigated RBD.

4. DISCUSSIONS

The following conclusions can be drawn from the results of the RBD sensitivity analysis:

4.1 Conclusions on the Reliability of the Investigated System

A. The reliabilities of blocks 31 and 3, as well as the overall system approach 1 asymptotically when the reliabilities of components increase (see Figure 3).

B. The reliability of block 312 increases exponentially if the reliability of the elements increases.

C. The reliability of block 3 is less than the reliability of block 31.

$$\mathbf{A} = \begin{bmatrix}
1 & -K_1 & -K_2 & -K_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -K_{211} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -K_{311} & -K_{312} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}; \quad (26)$$

$$\mathbf{B} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & K_C & K_D & K_E & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & K_G & K_H & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & K_L & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & K_N & K_O & K_P & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & K_S & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & K_V & K_W & K_X & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & K_Y & K_Z \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \quad (27)$$

4.2 Conclusions on the Sensitivity of Reliability of the Investigated System

D. The reliability of the system has the maximum sensitivity to the reliability of the elements Y and Z (see Fig. 4).

E. The reliability of the system has the least sensitivity to the reliability of the elements T and U (see Fig. 4).

F. The relative sensitivity of system reliability decreases if the reliabilities of the elements increase (see Fig 5 and 6).

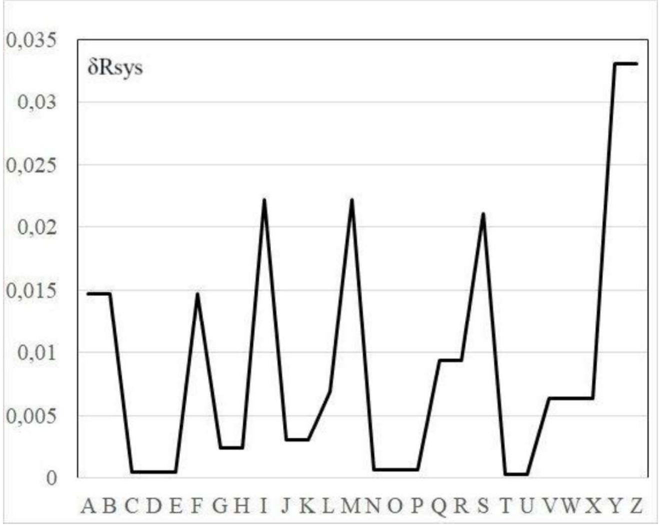

Fig. 4 Sensitivities of System Reliability ($r_i = 0.8$)

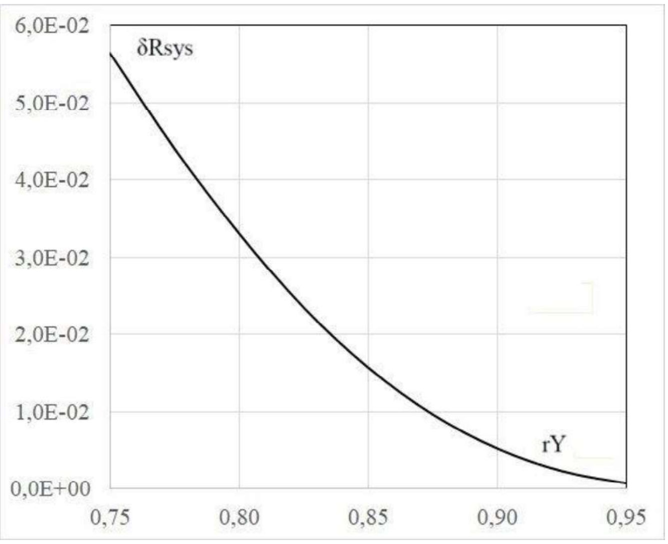

Fig. 5 Sensitivities of System Reliability Depends on Reliabilities of Components Y and Z

4.3 Conclusions on the Hierarchical Sensitivity Model of Reliability Block Diagram (HSMoRBD) method

The advantages of the HSMoRBD are the following:
G. The HSMoRBD is an easy-to-use algorithm.
H. The elements of coefficient matrices can be easily determined because they are typical ones.

I. The sensitivity matrix shows sensitivity coefficients not only for the entire system or process but for the subsystems or subprocesses as well.
J. The sensitivity structure og the coefficient is similar, thus substituting parameters makes the whole system typical or typified.

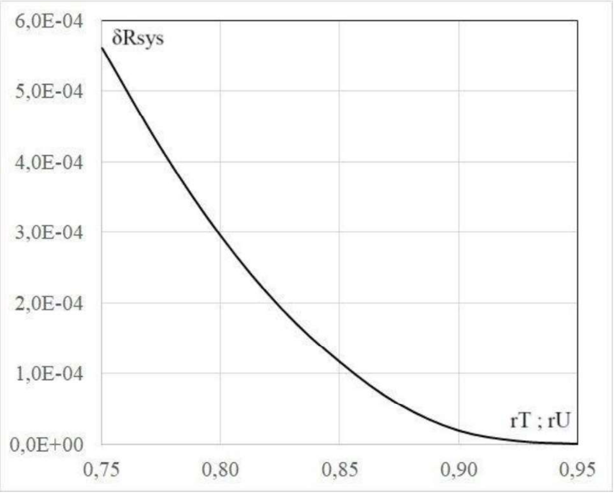

Fig. 6 Sensitivities of System Reliability Depends on Reliabilities of Components T and U

K. Based on Conclusions D and E, the author introduce the terms “***structural sensitivity***” and “***structural sensitivity coefficient***”.
The structural sensitivity coefficient character-izes the effect of a given component from constructional point of view. Its value is determined only by localization in the system – not its value – of the given component.

4. SUMMARY, FUTURE WORK

This paper proposed a new modular approach method called Hierarchical Sensitivity of Reliability Block Diagram (HSoRBD). Using the proposed method it is possible to determine the most critical elements of networks and network structure systems. The proposed method can be used to mathematical model-based investigation of reliability stability and capacity of high scale road traffic networks for their optimal control (see reference [4]).
In terms of directions of future research the Author planes to study of sensitivity and uncertainty analysis methodologies of technical systems, such as vehicle sensory network road traffic network, reliability

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