STRUCTURAL REDUNDANCY IN AUTOMOTIVE TRANSPORT

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ABSTRACT

The authors examine reliability of technical systems as a scientific category and an object of application of methodological and mathematical tools that help to assess the required performance, to find task relevant criteria and ways to switch on reserves. Priorities are structural redundancy, classification of its kinds, projection of calculated options on the features of automobile transportation. Demonstrated approaches are based on reliability theory, systems theory, laws of logic, Boolean functions.

ENGLISH SUMMARY

Background. *According to the dictionary of Russian language, «reliable» means trustworthy, loyal. Applied to a person, the term «reliability» is used as a characteristic of his positive qualities: punctuality, commitment, loyalty and responsibility. In technology, reliability is a property of a system to maintain its output parameters within acceptable limits, pledged at the design stage. In the business environment, reliability is indispensable for a successful business, is a key to stability of results, the dynamics of its development. Reliability as a scientific category can be treated differently. Regardless of the application object, much attention is always paid to the problem of improving reliability. To study it, a separate research area is formed which is reliability theory. Examples of basic works on it are cited, in particular, through a number of researches of domestic [3, 5, 13] and international [1, 11, 14] scientists. The theory of reliability of technical systems is probably the most studied one. Its methodology and conceptual apparatus are used, however, in other spheres. For example, the concept of «risk», as well as methods for predicting and reducing probability of risk events in technology have become a subject of the study within risk management and are used in the reliability analysis of production and economic processes [2, 15, 17]. The principles of calculating the reliability of technical objects are adapted to the calculation of the reliability of supply chains [4, 7, 12].*

Reliability of transport systems and transport processes also has methodological connection with reliability of technical systems, as redundancy is applied to improve the quality of delivery of goods and passengers, as well as in engineering. In addition, the analysis of reliability of automobile transportation is based on the methodical base of fundamentals of road safety, of technical operation of vehicles, of situation transportation management.

However, it should be appreciated that reliability theory of transport systems and processes has not been yet fully formed. Therefore it remains relevant to conduct research aimed at the development of its methodological, regulatory and information support, and this is directly reflected in the character of processes study in the field of automotive transport.

Objective. *The objective of the authors is to investigate reliability of transport processes and in particular methods of structural redundancy.*

Methods. *The authors use analytical method, description and mathematical calculations, reliability theory, systems theory, laws of logic, Boolean functions.*

Results.

Classification and combination of methods

Recommendations, proposed in the article, are based on the definitions of reliability and failure of the transportation process, set out in [6, 10]. According to them, the reliability of the operation of transport systems and transport processes is a complex property, which includes the system's ability to perform requirements agreed between the customer and the transportation service provider as for the number and condition of cargo, passenger safety and security of their luggage, compliance with schedule of the transport process, as well as maintaining and restoration of a given level of transport service. Non-compliance with the agreed requirements is a failure. Causes of failures can be a fault of the performer of transport technological operation or a malfunction of other participants in the process.

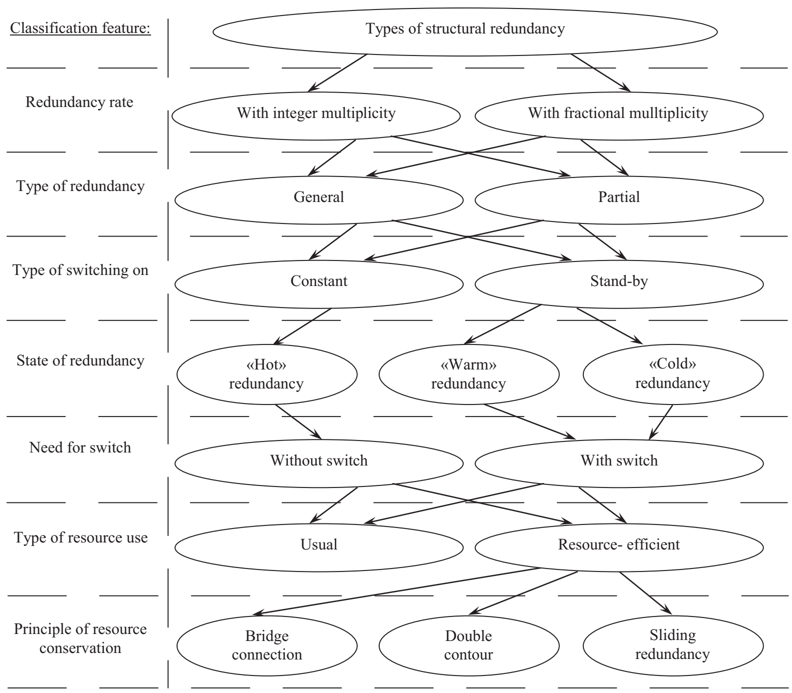
It is possible to improve the reliability of the transport process by introducing into its structure additional structural elements or their compounds. Input elements are called intermediaries-doubles, and the connections of duplicated structural elements are called redundant delivery channels. The principle of increasing reliability through the use of redundant elements is realized in the presence of any modern equipment. In [9], this approach is called structural redundancy.

There are schemes of general and partial redundancy, constant redundancy and stand-by redundancy, redundancy with integer and fractional multiplicity. The authors propose a classification of methods of structural redundancy of transport systems and processes, taking into account the mentioned features of technical systems redundancy and new classification criteria: type of resource use and principle of resource conservation (see Pic. 1).

Improving reliability of transport systems and transport processes is achieved by redundancy of a main delivery channel (-s) as a whole, or its individual elements. Hence, there are two types of structural redundancy: general and partial (element-wise). According to the method of redundant delivery channels switching on both general and partial types can be constant and stand-by. In case of constant redundancy main and all redundant channels operate simultaneously, from the time of execution of the first process step of the transport process. In case of stand- by redundancy redundant delivery channels are activated only after failure of main channels. Combinations of these methods are shown schematically in Pic. 2.

Constant redundancy is named loaded or «hot», and the unloaded state is characteristic of stand-by redundancy. When a redundant delivery channel is ready to almost instantly replace a failed main channel, it should be assumed that it is in a «warm» state. If some time is required to prepare a redundant channel to work (it should be «warmed up»), then such redundancy is in a «cold» state.

For normal operation of schemes of stand-by redundancy, a switch is required that is a device that in case of failure ensures the transition of a redundant delivery channel or its section, which is in a «warm»



Pic. 1. Proposed classification of methods of structural redundancy in automotive transport.

or «cold» state, to a functioning state. One of the main requirements for the switch is its speed, that is, that time for entering redundant delivery channels should not significantly affect the course of a transport process. It should also be noted that low reliability of switches as well as a large number of them negatively affect the overall result of transportation. Schemes of constant redundancy of transport process do not require the presence of a switch.

Regardless of the presence or absence of a switch, redundancy of transport process is also proposed to be differentiated by type of resource use. The inclusion of this classification feature is determined by the need for a classification feature of the structural element in labor costs, technology, energy resources, material values, necessary for technological operations of a transport process. As a rule, the amount of such costs is in direct proportion to the number of structural elements. Schemes of constant or stand-by redundancy are redundancy schemes with a conventional resource use. Redundancy schemes, providing the same or almost the same level of reliability with the help of fewer elements are classified as resource efficient.

Gain of reliability, reduced to one structural element, is higher in resource saving schemes. This is achieved by their special configuration or specificity of compounds that are present in redundancy schemes (bridge, double contour, sliding reserve). A combination of redundancy and the need for special mathematical apparatus of evaluating the reliability determine methods of structural redundancy in automotive transport: constant redundancy with integer multiplicity, stand-by redundancy, majority and resource-saving schemes.

Constant with integer multiplicity

Diagrams (a, c) in Pic. 2 illustrate the type of constant redundancy with integer multiplicity. Here main and redundant delivery channels operate simultaneously with the start of transportation. This redundancy is characterized by a Boolean function:

$$\varphi(x) = \bigcup_{i=1}^{z+1} x_i = x_1 \cup x_2 \cup \ldots \cup x_{z+1} \, , \qquad (1)$$

where $\phi\,(x)$ is a structural function of a transport process:

$$\phi\,(x) \begin{cases} 1 - \text{if failure of a transport process is not observed;} \\ 0 - \text{if failure of a transport process is observed.} \end{cases} \qquad (2)$$

Here $x = (x_1, x_2, \ldots, x_{z+1})$ is a vector of state of i-th delivery channel.

For a random Boolean variable, that is for Bernoulli random variable a structural reliability function of a transport process will take the form:

$$E\,\{\phi\,(x)\} = P, \qquad (3)$$

where P is a criterion of transport process reliability.

Based on the above expressions, criterion of transport process reliability by applying a general constant redundancy with integer multiplicity will be calculated according to the formula

$$P = E\{\phi(x)\} = 1 - \prod_{i=1}^{z+1} Q_i = 1 - \prod_{i=1}^{z+1} (1 - P_i)\, , \qquad (4)$$

where Q_i is a criterion of transport process failure;

P_i is a criterion of reliability of i-th delivery channel, including the main one.

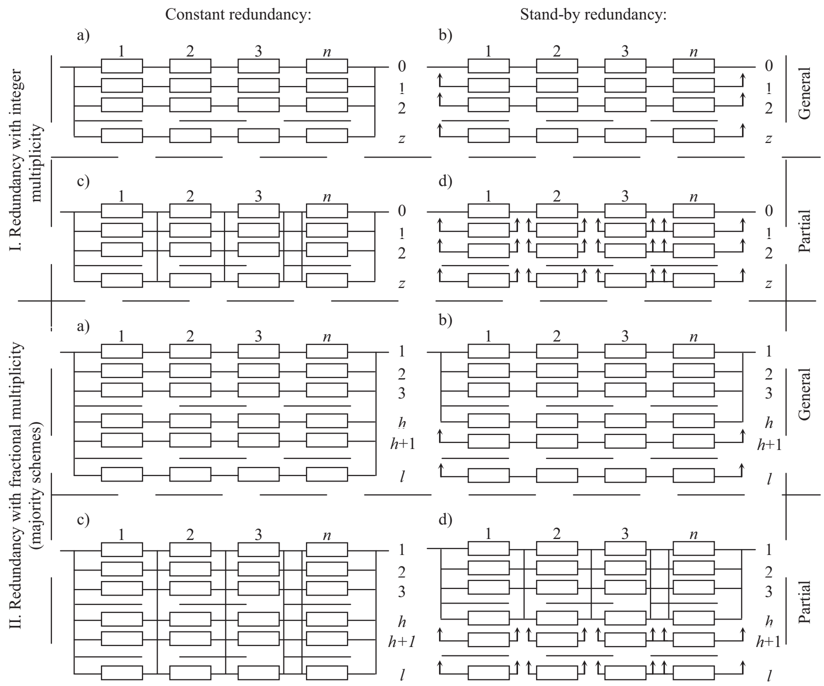
The same criterion for partial constant redundancy with integer multiplicity is determined by two variants, which are:

– series-parallel structure:

$$P = 1 - \prod_{j=1}^{z+1} \left(1 - \prod_{i=1}^{n} p_{ij} \right); \qquad (5)$$

– parallel- series structure:

$$P = \prod_{j=1}^{n} \left(1 - \prod_{i=1}^{z+1} \left(1 - p_{ij} \right) \right), \qquad (6)$$



I – Redundancy with integer multiplicity; II – Redundancy with fractional multiplicity;
(a) – General constant; (b) – Constant stand-by; (c) – Partial constant; (d) – Partial stand-by.

Pic. 2. Combination of structural redundancy methods.

where p_{ij} is a reliability criterion of structural element of a transport process.

In case of constant redundancy a transport process fails if all delivery channels fail. Therefore, this kind of structural redundancy has the following properties:

– With increasing number of redundant channels reliability of a transport process, ceteris paribus, increases;

– Reliability of a transport process as a whole is always greater than reliability of any delivery channel, including the best one.

In practice, constant redundancy with integer multiplicity for improvement of transport process reliability is used relatively infrequently, because it is not always possible to organize a parallel work of participants in the loaded redundancy mode, especially in the case of element-wise redundancy. Moreover, this redundancy has a high prime cost.

Majority schemes

Calculation of reliability of majority schemes (schemes of redundancy with fractional multiplicity) has its own specifics, because for failure-free operation of the transport process reliable operation of not less than (h) delivery channels of (l) total possible channels, including main and redundant channels, is required. Boolean function that characterizes this redundancy takes the values:

$$\phi(x) \in \begin{cases} 1, \text{if} \sum_{i=1}^{l} x_i \geq h \\ 0, \text{ if} \sum_{i=1}^{l} x_i \prec h. \end{cases} \quad (7)$$

The implication here is that failure-free operation of i-th delivery channel (its state (x_i)) and the presence of a failure of delivery channel are pairwisely incompatible events. They are mutually exclusive. For example, in case of mandatory work of two delivery channels out of three possible channels function $\phi(x)$ takes the form:

$$\phi(x) = (x_1 \cap x_2 \cap x_3) \cup (\overline{x_1} \cap x_2 \cap x_3) \cup$$
$$\cup (x_1 \cap \overline{x_2} \cap x_3) \cup (x_1 \cap x_2 \cap \overline{x_3}). \quad (8)$$

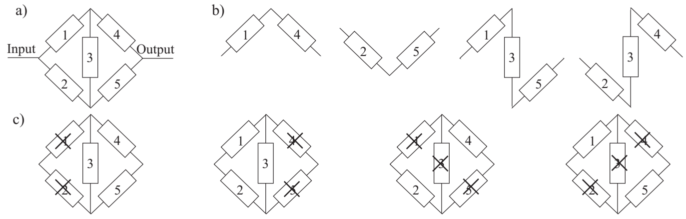
Transition from a Boolean function to the formula for calculating the reliability criterion of the transport process is carried out by means of the binomial distribution. For consideration of majority scheme «two delivery channels out of three» formula for calculating the value of (P) is obtained by the conversion of the probabilities of all its possible states, that is, using the binomial expansion:

$$(P+Q)^3 = P_1 \cdot P_2 \cdot P_3 + P_1 \cdot P_2 \cdot Q_3 + P_1 \cdot Q_2 \cdot P_3 + Q_1 \cdot P_2 \cdot P_3 +$$
$$+ P_1 \cdot Q_2 \cdot Q_3 + Q_1 \cdot P_2 \cdot Q_3 + Q_1 \cdot Q_2 \cdot P_3 + Q_1 \cdot Q_2 \cdot Q_3 = 1. \quad (9)$$

For majority redundancy schemes, numbering (l – h) redundant delivery channels, as well as (l - h) redundant elements of any of (h + n) structural elements of the main channels the binomial expression of possible states of a transport process will be written as (10). To simplify there is an accepted assumption on equal reliability of all structural elements of delivery channels:

$$(P+Q)^l = P^l + l \cdot P^{l-1} \cdot Q +$$
$$+ \frac{l \cdot (l-1)}{2!} \cdot P^{l-2} \cdot Q^2 + \frac{l \cdot (l-1) \cdot (l-2)}{3!} \cdot P^{l-3} \cdot Q^3 +$$
$$+ \frac{l \cdot (l-1) \cdot (l-2) \cdot (l-3)}{4!} \cdot P^{l-4} \cdot Q^4 + \ldots + Q^l = 1. \quad (10)$$

Majority redundancy schemes are used in practice quite often, as they provide a required level of reliability by a number of redundant delivery channels, which is less than the number of channels required by the customer.



Pic. 3. Flowchart (a), minimum ways (b) of bridge connection.

Stand-by redundancy

The principle of calculating the reliability of a transport process by using stand-by redundancy is based on the total probability formula. As an example, we took a scheme with one main (A) and one redundant delivery channels (Б). With account of equal reliability of delivery channels, failures in the transport process will be observed under the following hypotheses: a channel failure (A) during the time (t) was not observed; channel failure (A) occurred at a time (τ), and a channel (Б) being intact until substitution (τ), worked smoothly over time (t - τ).

Based on the formula of total probability of those hypotheses, reliability criterion of the transport process, which is stand-by redundant for the time (t), is equal to:

$$P(t) = P_A(t) + P_{Б/А}(t,\tau)\cdot Q_A(t), \qquad (11)$$

where P_A (t) is a probability of failure- free operation of a main delivery channel during (t); $P_{Б/А}$ (t, τ) is a probability of a failure-free operation of a redundant delivery channel during (t) assuming that failure of a main channel occurred at (t); Q_A (t) is a probability of main delivery channel failure during (t).

To determine the value of P_A (t) we apply a principle of calculating the probability of failure-free operation of technical objects, based on testing of samples of the same type:

$$P_A(t) = \frac{N_0 - n(t)}{N_0}, \qquad (12)$$

where N_0 is a number of samples at the beginning of testing, pcs; n (t) is a number of samples that fail during specific time interval, pcs.

Calculation of the value PA (t) is proposed, based on the principles of determining the reliability criterion of a transport process [8]. If we take the total number of demands for transportation, accepted for execution during the period, as the number of samples at the beginning of testing (N_0), and if we take the the difference between the total number of demands for execution, and the number of requests performed during the same period of time without violating the requirements of the customer, as a number of samples that failed, n (t), the formula (12) takes the form:

$$P_A(t) = \frac{N_0 - n(t)}{N_0} = \frac{M - \left(M - \sum_{j=1}^{M} F_j\right)}{M} = \frac{\sum_{j=1}^{M} F_j}{M}, \qquad (13)$$

where M is a total number of applications for transportation accepted for execution during the considered period, units; $\sum_{j=1}^{j} F_j$ is a number of requests, performed for the same period of time without violating the requirements of a customer, units.

To determine the value of $P_{Б/А}$ (t, τ) in the transport process it is also proposed to use a mathematical apparatus of reliability theory of technical systems:

$$P_{\ /}(t,\tau) = \sum_{i=1}^{\frac{t}{\Delta\tau_i}} a(t_i)\cdot\Delta\tau_i\cdot P\ (t,t_i), \qquad (14)$$

where *a* (t_i) is a failure rate of a system or a process, h^{-1}; $\Delta\tau_i$ is a time interval, h; *P* (*t*, t_i) is a criterion of reliability and failure of a redundant channel for a time ($t - t_i$).

Based on the transformation of the formula (13), we obtain an expression for finding a (t) of the transport process, which is equivalent to the expression for definition of a (t) of a technical object:

$$a(t_i) = \frac{n(t)}{N_0\cdot\Delta\tau_i} = \frac{M - \sum_{j=1}^{M} F_j}{M\cdot\Delta\tau_i}. \qquad (15)$$

Then we obtain the desired formula:

$$P_{Б/А}(t,\tau) = \sum_{i=1}^{\frac{t}{\Delta\tau_i}}\left(\frac{(M - \sum_{j=1}^{M} F_j)\cdot\Delta\tau_i}{M\cdot\Delta\tau_i}\cdot\frac{\sum_{j=1}^{M} F_j}{M}\right) = \sum_{i=1}^{\frac{t}{\Delta\tau_i}}\left(\frac{M\cdot\sum_{j=1}^{M} F_j - \sum_{j=1}^{M} F_j^2}{M^2}\right) =$$

$$= \sum_{i=1}^{\frac{t}{\Delta\tau_i}}\left(\frac{\sum_{j=1}^{M} F_j}{M} - \frac{\sum_{j=1}^{M} F_j^2}{M^2}\right) = \sum_{i=1}^{\frac{t}{\Delta\tau_i}}\left[P_Б(t,t_i) - P_Б^2(t,t_i)\right]$$

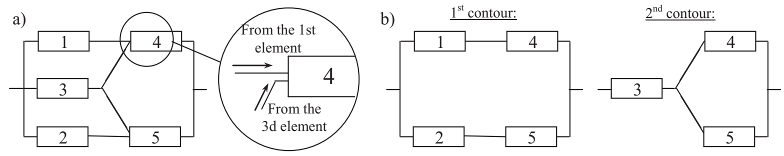
$$= \sum_{i=1}^{\frac{t}{\Delta\tau_i}}\left[P_Б(t,t_i)\cdot(1 - P_Б(t,t_i))\right] = \sum_{i=1}^{\frac{t}{\Delta\tau_i}}\left[P_Б(t,t_i)\cdot Q_Б(t,t_i)\right]. \qquad (16)$$

It should be noted that scheme of stand-by redundancy of a transport process has one major limitation that is that the switching device is deemed to be ideal in terms of reliability. In practice, any redundant connection that works using the principle of substitution, requires the use of switching devices in each of the working and redundant chain. In the transport process the function of a switch is performed by a traffic controller carrying out online monitoring, which develops and implements control actions to prevent failures or to eliminate them with minimal consequences. In terms of reliability switches have a serial connection to the redundant delivery channels, so the formula for calculating the reliability criterion of the transport process, which is stand-by redundant, is adjusted as follows:

$$P(t) = P_{l-h}(t) + P_{?}\cdot\sum_{i=1}^{\frac{t}{\Delta\tau_i}}\left[P(t,t_i)\cdot Q(t,t_i)\right]\cdot Q_{l-h}(t), \qquad (17)$$

where P_n is a probability of failure-free operation of a switch.

These methods of structural redundancy are a variety of methods to improve the reliability with conventional resource use. The following methods are resource efficient.



Pic. 4. Scheme of transport process redundancy with double contour.

Bridge connections

Such a connection (Pic. 3) cannot be reduced to a more simple equivalent scheme by folding series and parallel chains of structural elements.

A scheme shown in Pic. 3 will be functional when at least one minimal way from input to output operates. A complete set of minimal ways is shown in Pic. 3 b. It consists of a subset of elements $\{x_1; x_4\}$, $\{x_2; x_5\}$, $\{x_1; x_3; x_5\}$, $\{x_2; x_3; x_4\}$. The structural function of a bridge connection, expressed through minimal ways, can be written as:

$$\varphi(x_1,...,x_5) = (x_1 \cap x_4) \cup (x_2 \cap x_5) \cup \cup (x_1 \cap x_3 \cap x_5) \cup (x_2 \cap x_3 \cap x_4). \quad (18)$$

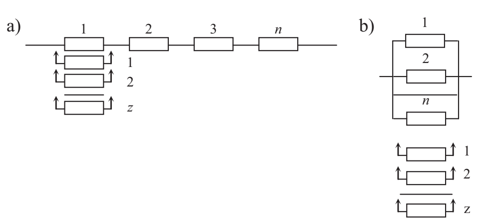
Reliability criterion of the transport process, structural elements of which have bridge connection, reflects the probability that a Boolean function (18) is equal to one. To calculate this expression it is proposed to apply the method of decomposition of Boolean functions [16]. Its essence lies in the decomposition of Boolean functions with respect to any element that enables the transformation of an irreducible scheme in parallel-series or series-parallel.

Selection (fixation) of the structural element for further decomposition of the function $\phi(x_i)$ does not matter, because the value of reliability criterion of the transport process does not depend on the resulting scheme configuration, even if we do not take a limitation with respect to equal reliability of elements. Therefore, the formula for calculating reliability of a bridge connection in the transport process is as follows:

$$P = p_1 \cdot \left[1 - \left[1 - (1 - q_2 \cdot q_3) \cdot p_5\right] \cdot q_4\right] + q_1 \cdot p_2 \cdot \left[1 - (1 - p_3 \cdot p_4) \cdot q_5\right] =$$
$$= p_2 \cdot \left[1 - \left[1 - (1 - q_1 \cdot q_3) \cdot p_4\right] \cdot q_5\right] + q_2 \cdot p_1 \cdot \left[1 - (1 - p_3 \cdot p_5) \cdot q_4\right] =$$
$$p_3 \cdot (1 - q_1 \cdot q_2) \cdot (1 - q_4 \cdot q_5) + q_3 \cdot \left[1 - (1 - p_1 \cdot p_4) \cdot (1 - p_2 \cdot p_5)\right] =$$
$$p_4 \cdot \left[1 - \left[1 - (1 - q_3 \cdot q_5) \cdot p_2\right] \cdot q_1\right] + q_4 \cdot p_5 \cdot \left[1 - (1 - p_1 \cdot p_3) \cdot q_2\right] =$$
$$= p_5 \cdot \left[1 - \left[1 - (1 - q_3 \cdot q_4) \cdot p_1\right] \cdot q_2\right] + q_5 \cdot p_4 \cdot \left[1 - (1 - p_2 \cdot p_3) \cdot q_1\right], \quad (19)$$

where $p_{1,..,5}$, $q_{1,..,5}$ are respectively criteria of reliability and failure of the 1st,…,5th structural element of the transport process.

The use of bridge connections for redundancy of the transport process at a comparable level of reliability allows to halve the need for structural elements in comparison with redundancy schemes of conventional resource use.



Pic. 5. Scheme of transport process redundancy with sliding redundancy with series (a) and parallel (b) connection of elements of the main delivery channel.

Scheme with double contour

Transport process may include elements, numbering not one, but two «inputs» (see Pic. 4).

In this redundancy scheme operation of channels 1–5 and 2–4 is excluded. Consequently, the connection of elements (1) and (2) with an element (3) is not possible. In fact, within this scheme two independent contours are enacted (see Pic. 4. b). Method of calculating the reliability of such a connection is based on the use of Bayes' theorem: if (A) is an event, depending on one of two mutually exclusive events (B_i) and (B_j), of which at least one certainly occurs, then the probability of occurrence of an event (A) is equal to $P(A) = P(A$, provided $B_i) \times P(B_i) + P(A$, provided $B_j)$.

We denote the event (A) as a failure of the transport process, and events (B_i) and (B_j) through failures as respectively failure-free operation and failure of the structural element (x), which determines reliability of the transport process. Then the formulation of Bayes' theorem in symbolic terms will be as follows:

P (failure of a process) = *P* (failure of a process, at fault-free (*x*)) × *P* ((*x*) fault-free) +*P* (failure of a process, at faulty (*x*)) × *P* ((*x*) fault-free). *(20)*

If for (x) we take the third structural element (see Pic. 4 a), the formula for calculating the reliability of the transport process takes the form:

$$Q = (1 - P_4) \times (1 - P_5) \times P_3 + +(1 - P_1 \times P_4) \times (1 - P_2 \times P_5) \times (1 - P_3). \quad (21)$$

We clarify: the need for the use of schemes with double contour to improve reliability of the transport process is determined by the specificity of automobile transportation technology, as well as by the limitations implied by traffic rules.

The use of sliding redundancy

With this redundancy any of the redundant elements may substitute any element of the main delivery channel. After substitution a redundant element becomes main, and in case of failure it may be substituted with any of the remaining redundant elements (see Pic. 5).

This method of improving reliability of the transport process is similar to the principle of increasing reliability using element-wise stand-by redundancy. So the calculation of reliability criterion of the transport process, the structure of which uses sliding redundancy, is made with (13, 16, 17). Although the method is effective, its use in practice is limited by the following reasons:

– *the need for highly reliable switch, the presence of the «human factor»;*

– *implementation of redundancy requires for presence of similar elements in the main delivery channel, that in view of the technological specifics of the transport process is difficult, and is even impossible in some cases.*

Conclusions.

1. More and more studies confirm the urgency to develop methodological, regulatory and information support of reliability of transport systems and processes, including by virtue of structural redundancy.

2. Introduction of additional structural elements or their connections in the transport process increases its reliability. Such elements become mediators-doubles, and connections of duplicating structural elements become redundant delivery channels.

3. The proposed classification of methods of transport process structural redundancy takes into account redundancy features of technical systems (multiplicity, type, state, and way of redundancy switching on, the need for a switch) and new classification features (type of resource use and resource conservation principle). Combination of methods and the need for special mathematical apparatus to evaluate reliability determine methods of structural redundancy in automotive transport sector, offered in the work: constant redundancy with integer multiplicity, the use of stand-by redundancy, majority and resource-efficient schemes.

4. The mathematical apparatus of the method of constant redundancy with integer multiplicity is best suited to engineering calculations. It provides a gradual simplification of the parallel-to-serial and serial-to-parallel connections of elements, and the use of binary logic formulas greatly simplifies the calculations. However, the implementation of the method is related to the high costs of keeping the reserves.

5. Majority redundancy schemes enable to use fewer redundant elements per one element under redundancy as compared to the schemes of constant redundancy with integer multiplicity. Method of calculating the reliability of majority schemes is based on the definition of the structural function of the transport process in Boolean variables and its subsequent transformation into a formula of reliability using the binomial distribution.

6. The method of computing the reliability of stand-by redundancy schemes is based on the formula of total probability of hypotheses on failure-free operation and failures of redundant delivery channel and delivery channel under redundancy. It takes into account the obligatory presence of a switch in a scheme having a serial connection to the channel under redundancy.

7. The principal difference of resource-efficient schemes using bridge connections, double contour or sliding redundancy is the absence of a parallel-to-serial and serial-to-parallel connection of elements. This ensures the advantage of reliability per one structural element of the transport process and as a consequence provides saving in production resources used to ensure reliable operation of the network.

Keywords: *reliability theory, structural redundancy, classification of methods, redundant delivery channels, reliability hypotheses, reliability of transport process, motor transport.*

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