INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING (IJAME)
ISSN: 2229-8649 e-ISSN: 2180-1606
VOL. 18, ISSUE 2, 8814 – 8824
DOI: https://doi.org/10.15282/ijame.18.2.2021.19.0675

ORIGINAL ARTICLE

Research of Determining Low-Reliability Elements of Multiple-Flows Compressed Air Braking System Based on Goal-Oriented (GO) Methodology

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ABSTRACT – The multi-flows pneumatic braking system is one of the modern braking systems equipped with truck vehicles which is a very complex system consisting of many elements connected in series or parallel. The reliability of the braking system has a significant influence on safety and the ability to manoeuvre. The study of identifying low-reliability elements in the brake system is of great significance to improve the efficiency of maintenance and repair. This article shows the research results that determine low-reliability elements of the multi-flows pneumatic brake system based on GO methodology, and allow to examine each element's reliability and the complex system. The reliability assessment model is built based on GO theory and statistics data collected at the used units about the frequency of damage, ability, and time to repair and restore the assemblies in the brake system. By using this model, the reliability of the assemblies and the whole system can be determined at any point in time relative to the actual operating time of the brake system. The article's research results can be applied for surveying other components' reliability and complex systems such as steering or suspension systems.

ARTICLE HISTORY
Received: 1st Feb 2021
Revised: 3rd May 2021
Accepted: 13th July 2021

KEYWORDS
Reliability;
Automotive pneumatic brake system;
Goal-oriented methodology

NOMENCLATURE

$P_0(t)$	non-failure working probability of the functional operator
$P_R(t)$	reliability of the functional operator
$\lambda_{i/j}$	failure intensity (number of failures per timing unit)
$\mu_{i/j}$	maintenance intensity (number of maintenance per timing unit)
R	output signal
C	operator itself
S	input signal
$P_S(t)$, $P_C(t)$, $P_R(t)$	available working probabilities of S, C, R at time t

INTRODUCTION

For clusters and systems, especially those that require very high safety during operation, such as nuclear power plant complexes, techniques to evaluate the probability of non-failure work play an important role [1]. Some methods have been used, such as Event Tree Analysis (ETA), Fault Tree Analysis (FTA), and Monte-Carlo simulation (MCs). We can mention a few examples, such as in [2] assessing railway accident risk through ETA, the FTA method to analyse the reliability of the starting system in automobiles [3], the MCs method is used in [4] to launch vehicle design and requirements verification. The above methods have some disadvantages, such as being very difficult to apply to complex systems. Building a reliable model is very difficult due to low similarity with natural physical systems; huge computation time is spent.

To overcome the disadvantage of the above method, the goal-oriented (GO) method is proposed as an alternative. The GO method is used for the reliability analysis of success-oriented complex systems [5]. It was developed initially for safety analysis and nuclear weapons and missile systems. Later, due to its enormous availability, it was modified and refined for nuclear power systems and other systems on civil aircraft and automobiles. The essence of the GO method is a graphical mapping method that allows describing the structure and working principle of an actual physical system with a complex structure. Therefore, it enables users to set up a mathematical model to determine the elements' reliability and the entire system accurately. It is possible to propose solutions to change measures of technical impact, spare-parts management, or optimise the reliability of assemblies and components during the design and manufacture process [6].

The braking system is one of the essential systems in an automobile. It helps to adjust the speed, stop the car, and ensure passengers and goods' safety on the vehicle. Thus, the braking system's reliability is an essential criterion for the safe movement of the vehicle, thereby assessing the quality of the vehicle's operation. Nowadays, the assessment of the braking system's reliability, the assemblies, and other systems on the truck to improve the operation's efficiency has an essential meaning. Any element of the braking system that is not working correctly and with low reliability can make the braking system inoperable or inadequate to ensure people and vehicles' safety, especially with popular braking systems

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such as pneumatic braking systems. Therefore, the analysis and determination of low-reliable elements in the braking system in general, multi-flows pneumatic braking system in particular, and timely maintenance and repair measures are essential.

THEORY OF GOAL-ORIENTED METHOD

The GO model is the system's reliability model, which is established by linking the GO operators together by signal lines to suit that system's hierarchical structure and functions. From there, evaluate the system's reliability according to its process.

Basic Types of Operators for GO Method

Operators are the units that describe the elements of the system according to their function or describe the logical relationships between the signal streams. They are divided into three categories: function operators, logical operators, and auxiliary operators. Each operator has 3 basic properties: data, symbols, and mathematical formulas. Figure 1 below introduces the symbols of commonly used target-oriented operators, the symbols, in turn, represent the input signal, the i_{th} input signal ($i = 1,2, .., M$), the target direction operator, and the output signal itself [6].

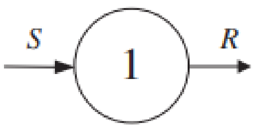
Instantly available formulas that determine the non-failure probability reliability of the function operator of a GO model with multiple failure modes are:

$$P_0(t) = \frac{1}{1+\sum_{j=1}^{n} \lambda_j/\mu_j} + \sum_{i=1}^{n} \frac{\prod_{j=1}^{n} (S_i+\mu_j)}{S_i \prod_{j\neq i}^{n} (S_i - S_j)} e^{S_i t} \quad (1)$$

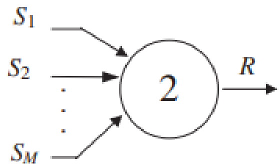
$$P_R(t) = P_0(t) \quad (2)$$

where $P_0(t)$ is the non-failure working probability of the functional operator at time t; $P_R(t)$ is the reliability of the functional operator at time t; $\lambda_{i/j}$ and $\mu_{i/j}$ are failure intensity (number of failures per timing unit) and maintenance intensity (number of maintenance per timing unit) of failure type the ith or jth ($j \neq i$) of the element; s_i is the negative real solution of the function:

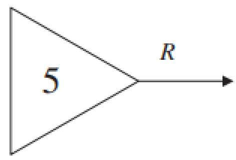
$$\prod_{i=1}^{n} (S + \mu_i) + \sum_{i=1}^{n} \lambda_i \prod_{j \# i} (S + \mu_j) = 0 \quad (3)$$



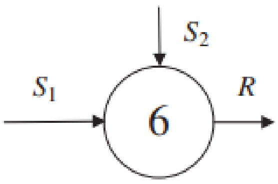
(a) Type 1



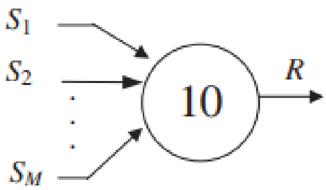
(b) Type 2



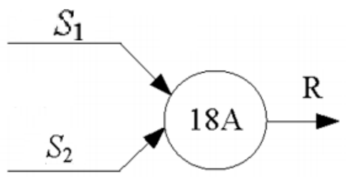
(c) Type 5



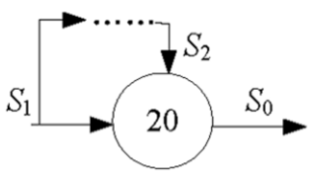
(d) Type 6



(e) Type 10



(f) Type 18A



(g) Type 20

Figure 1. Basic types of operators used in GO method.

Type 1 operator

The type 1 operator represents the elements with two states, the working state (for the passage of the signal) and the failed state (for no signal flow). The symbols R, C, and S represent the output signal, operator itself, and input signal. Probability formula of type 1 operator [6] is given as:

$$P_R(t)=P_S(t).P_C(t) \quad (4)$$

where, $P_S(t),P_C(t),P_R(t)$ in turn, is the available working probabilities of S, C, R at time t.

Type 2 operator

The type 2 operator represents the logical "OR" relationship between the input signals and an output signal. Symbols represent the ith input signal and output signal i ($i=1,..,M$). Probability formula of type 2 operator [6] is given in Eq. (5)

$$P_R(t)=1-\prod_{i=1}^{M}(1-P_{Si}(t)) \tag{5}$$

where $P_R(t)$, $P_{Si}(t)$ in turn, is the available working probability of R,S_i at time t.

Type 5 operator

The type 5 operator represents single elements of the input signal, which often act as the system's input signals, usually as energy sources. The symbols R, C represent the output signal and the operator itself, respectively. Probability formula of type 5 operator [6] is in Eq. (6):

$$P_R(t)=P_C(t) \tag{6}$$

where $P_C(t),P_R(t)$ in turn, is the available working probability of C, R at time t.

Type 6 operator

The type 6 operator represents the elements that receive the signal to work with. Symbols R,C,S_1,S_2 represent the output signal, the operator itself, and 2 input signals. In which S_2 signal activates the operator, allowing the signal S_1 to pass through the element. Probability formula of type 6 operator [6] is in Eq. (7).

$$P_R(t)=P_{S1}(t).P_{S2}(t).P_C(t) \tag{7}$$

where, $P_{S1}(t),P_{S2}(t),P_C(t),P_R(t)$ in turn, is the available working probability of S_1,S_2,C, R at time t.

Type 10 operator

Operator type 10 represents the logical "AND" relationship between the input signals and an output signal. Symbols R, S_i represent the ith input signal and output signal i ($i=1,.., M$). Probability formula of type 10 operator [6] is:

$$P_R(t)=\prod_{i=1}^{M}P_{Si}(t) \tag{8}$$

where $P_R(t),P_{Si}(t)$ in turn, is the available working probability of R,S_i at time t.

Group of Operators for Redundant Structure

The basic redundant structure includes the main equipment group and redundant equipment group [7]. In particular, the group of backup equipment is only done when the main equipment group is damaged. The redundant structure group includes the logical operator of type 18A and the auxiliary operator type 20. The logical operator of type 18A is used to represent the logical relation of the redundant structure, and the auxiliary operator of type 20 is used to describe the signal current of conditional operation [8]. The combination of these two operators and the groups of devices in the structure represents the system's parallel properties and is shown in Figure 2.

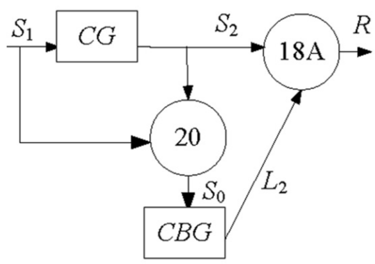


Figure 2. Group of type 20 operator and type 18A operator for the redundant structure.

With $P_{Si}(t)$ is the non-failure probability of S_i at time t ($i = 0, 1, 2, 3$); $P_R(t),P_{TBDP}(t)$ are the non-failure probabilities of R and the spare device group, respectively; $\lambda_{S2}(t),\lambda_{S3}(t),\lambda_R(t)$ is the failure intensity of S_2,S_3,R at time

t; $\mu_{S2}(t)$,$\mu_{S3}(t)$,$\mu_R(t)$ is the maintenance intensity of S_2,S_3,R at time t. Probability formula of the group operator for the redundant structure is given in Eq. (9).

$$\begin{cases} P_R(t)=P_{S2}(t)+P_{S3}(t) \\ P_{S0}(t)=P_{S1}(t)-P_{S2}(t) \\ P_{S3}(t)=P_{S0}(t).P_{TBDP}(t) \end{cases} \tag{9}$$

Signal flow

Signal flow describes the logical process or flow of a working medium (such as liquid, gas, and electric current). It describes the relationship between the GO operator, its input, and output. Base on the signal currents, the operators are linked together in a defined sequence and build a GO model.

Identify elements with low reliability in the system

In a system, the elements of different reliability have different effects on the system's performance. The reason lies in the relationship between each element with the rest of the elements and the position of that element in the system. For the determination of components, element assemblies with low reliability with levels of influence on the system's overall failure, the GO method allows qualitative analysis to determine the minimum cut set in the system. The minimum cut sets are the only combinations of failures that make system failures. If one or more association elements are removed, the failure of the remaining elements in the combination will not damage the system. The order of a minimum cut set is at least equal to the number of aspects of it. Identifying minimum cut sets is the basis for identifying potential risks and weak links in the system. The basic steps for performing a GO qualitative analysis are recognised as the following [8]:

Step 1: Set the non-failure probability of the functional operators in the GO model to 0 in turn, while the non-failure likelihood of the remaining operators is kept constant. In either case, if the system's non-failure probability equals 0 then the function operator set to zero failure probability will be the 1st-order minimum cut set.

Step 2: Set the non-failure probabilities of two of the remaining functional operators in the GO model to 0, and the non-failure probabilities of the remaining operators are kept constant. In either case, if the non-failure likelihood of the system is zero, then the two functional operators set the zero probability of failure will be the 2nd-order minimum cut set.

Step 3: Similar to the above steps, a higher-order minimum cut set is determined. Usually, higher-order minimum cut sets have a tiny probability, so qualitative analysis of the GO for systems specifies only up to the 2nd-order minimum cut set. In a qualitative analysis of the system, the system reliability based on the non-failure probability is based on a GO algorithm. With this algorithm, the non-failure working probability of each output signal in an operator is calculated directly according to the GO operator's probability formula.

EXAMPLES OF DETERMINING LOW-RELIABILITY ELEMENTS IN THE SYSTEM

The following are examples of low-reliability element determination in some typical subsystems in multi-flows pneumatic braking systems (Figure 3). The data collected according to the survey sample is the truck vehicle.

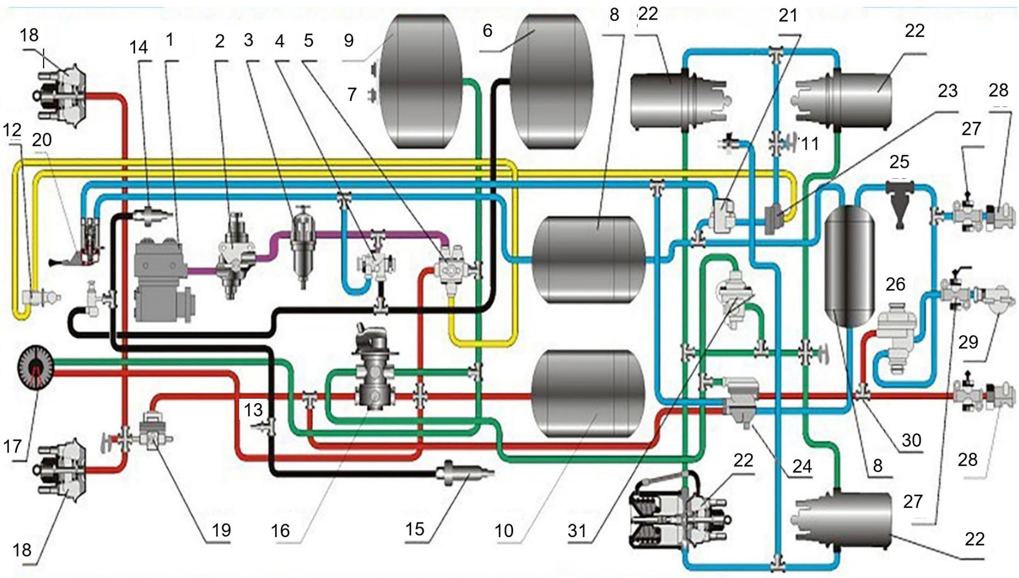


Figure 3. Diagram of the pneumatic braking system on truck vehicle.

Simple Parallel System

Selecting the control circuit for the under valve of the 2-level braking valve on the truck to research. The following assumptions are satisfied:

i. See the system as independent, ignoring correlations for other circuits.
ii. Consider the driver's impact and the mechanical components that act from the driver to the upper valve of the 2-level braking valve as a cluster. This cluster probability of no failure is equal to the component elements' probability product [9].
iii. The probability of success of the pistons is considered to be 1.
iv. Only consider elements and systems in a working or failed state.
v. The minimum cut sets of the system are considered independent of each other.

Building GO model

Structure: The structure of the 2-level braking valve is shown in Figure 4. Based on the function and properties of the circuit, the main structure of the circuit is composed of an upper valve cluster (including upper 29 valve, return spring 13), pushrod 18, compressed air tank for the supply of compressed air to door II, control source assembly (driver action, lever 1, roller 4, roller 5, roller 6, nut 8, screw 11, 9 elastic discs, piston 30, the cushion 31, seal 33).

System features: the system in question has a redundant structure (the basic redundant structure consists of a group of main equipment and a group of redundant equipment. Only performed when the main unit group is damaged)

System interface: The input signal of the system is controlled by the driver. When the driver applies the brake, the control piston signal 15 is the system's output.

Principle of working successfully: There is an impact to move the piston 15 when the driver performs the brake with the 2-level braking valve.

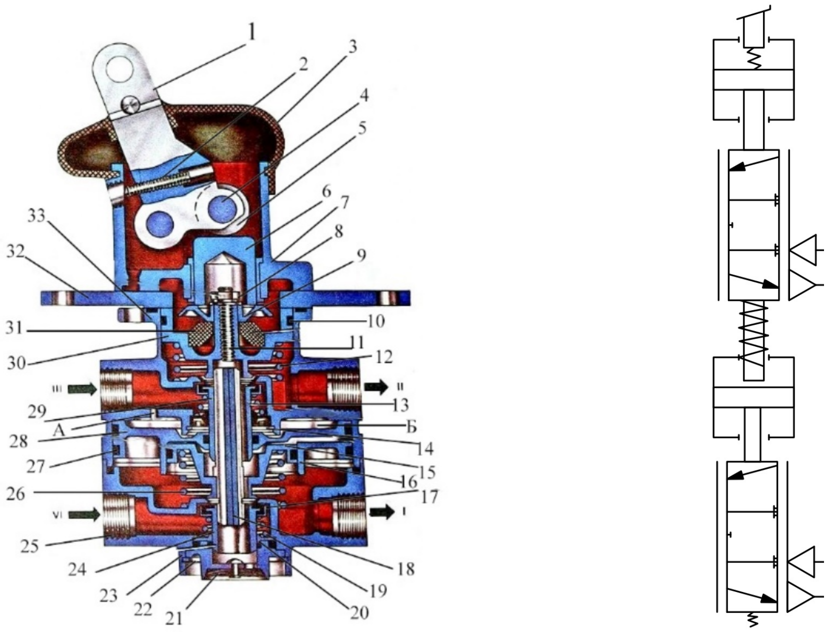


Figure 4. Structure of a 2-level braking valve.

GO model set-up

Based on the system analysis results above, the GO operators are selected as shown in Table 1, and the GO diagram is set up in Figure 5.

Table 1. Types of GO operators in the model.

Order	Components	Type of GO operators
1	Control source cluster	5
2	Compressed air tank	5
3	Pipe line	1
4	Upper valve	6
5	The operating condition of auxiliary group	20
6	Thrust 18	1
7	Logic relationship of auxiliary structure	18A

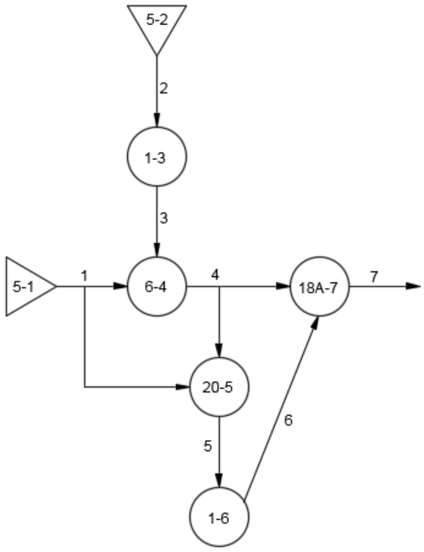


Figure 5. Model of target direction for the lower valve control circuit of the 2-level braking valve on the truck vehicle.

Data reliability of the system's elements according to GO method

We can determine the non-failure probabilities of each element after operation distance 5000 km base on statistical data collected by using the truck's document diary. The results are shown in Table 2 as follows:

Table 2. Parameters to evaluate the reliability of the elements.

Order	Components	Failure intensity (damage/hour)	Maintenance intensity (times / hour)	Probability of working successfully
1	Control source cluster	0.002	0.012	0.9903419
2	Compressed air tank	0.004	0.045	0.9822616
3	Pipe line	0.015	0.028	0.9325145
4	Upper valve	0.0012	0.008	0.9941359
6	Thrust 18	0.0008	0.0015	0.9960229

Thus, with GO method, we can ultimately determine the probability of the operational success of each element in the system and the whole system allowing optimised maintenance, repair, and replacement spare-part planning. This is one of the points showing the applicability of the GO method to many different complex systems.

According to the GO method, the system's part with low reliability is determined through a minimum cut set by qualitative analysis of the system. According to the direct algorithm, we have the formulas to use for the system:

$$\begin{cases} P_{R7}(t)=P_{R4}(t)+P_{R6}(t) \\ P_{R5}(t)=P_{R1}(t)\text{-}P_{R4}(t) \\ P_{R6}(t)=P_{R5}(t).P_{C6}(t) \\ P_{R4}(t)=P_{R1}(t).(P_{C4}(t).P_{R3}(t)) \end{cases} \quad (10)$$

Based on the features of the basic redundant structure, it is easy to define GO operator 1 as a 1-order minimum cut set, the 2-order minimum cut set includes Group of GO operator 2 and 5; Group of elements with objective orientation 3 and 5. Researching results are determined and presented in Table 3.

Table 3. Results of GO qualitative analysis for the system.

Order	Element ID number	Broken elements	Probability of failure
1	1	Control source cluster	0.0096581
2	2, 5	Compressed air tank, thrust	0.0000705
	3, 5	Upper valve, thrust	0.0000233

The results in Table 3 show that part number 1 (Control source cluster) is most likely to fail during the working process, so take special care during the operation.

Simple Serial System

Select the circuit that drives the middle and rear axles of the braking system on the truck to inspect the circuit with no brakes. The following assumptions are satisfied:

i. To simplify the selected model, only analyse to determine the circuit's reliability in the non-braking state.
ii. Consider the mid-and rear-bridge brake drive circuit of the stopping brake system as a stand-alone system; The lead branches, connections, and relationship to the brake release circuit and other drive circuits are ignored [10].
iii. The probability of successful working of pipes and connectors is considered to be the one.
iv. Only consider elements and systems in a working or failed state.
v. The minimum cut sets of the system are considered independent of each other.

Building GO model

Structure: The middle and rear axle brake drive circuit includes the following elements: pneumatic tanks, reverse hand brake valve, accelerator valve, vent valve, brake bulbs, and mid-bridge energy storage, the brake cylinders, and rear-wheel power accumulator. The structure diagram of this circuit is shown in Figure 6, and the principle of operation diagram can simplify it as in Figure 7 below:

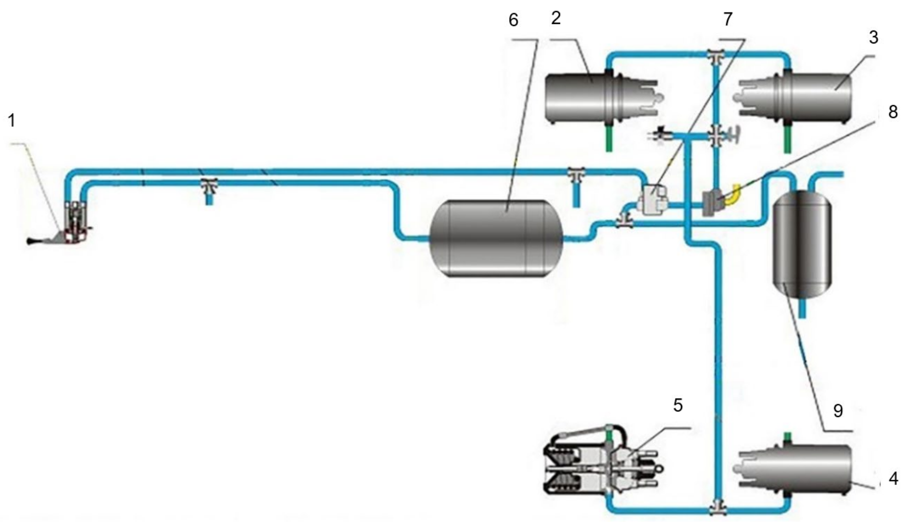


Figure 6. Structure of the circuit that drives the middle and rear axle brake of the hand-brake system on the truck vehicle.

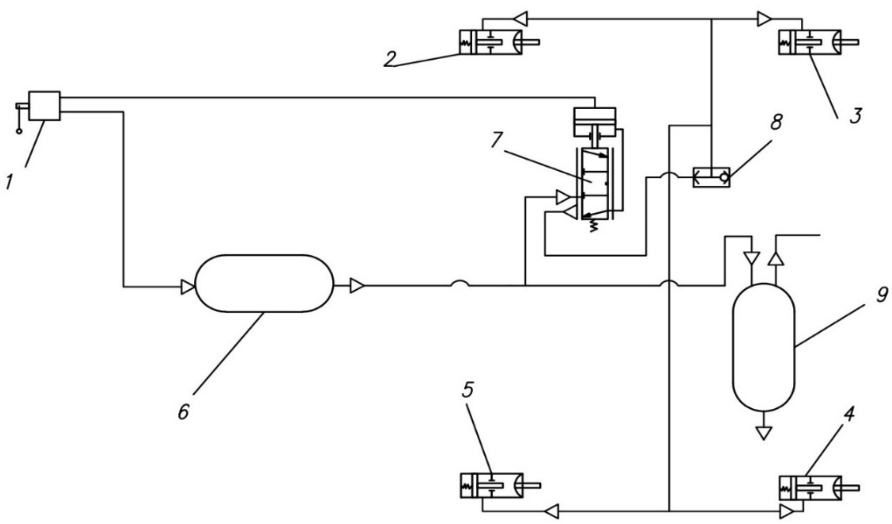


Figure 7. Diagram of driving circuit of the middle and rear axle brake of the braking system on the truck vehicle.

System features: From the analysis results above, we can determine that the system uses shared signals.

System interface: The input signal of the system is compressed air from 2 tanks. When the driver performs the brake, the compressed air exits the wheel's brake bulb accumulators through the bypass valve, and the acceleration valve is the output signal of the system.

Principle of working successfully: When no braking, the compressed air is filled in the middle and rear axle brake bulbs.

GO model set-up

Based on the system analysis results above, the GO operators are selected as shown in Table 4, and the GO model is illustrated in Figure 8.

Table 4. Types of GO operators in the model.

Order	Components	Type of GO operators
1	The impact of the driver	5
2	Compressed air tank 1	5
3	Compressed air tank 2	5
5	Hand braking reverse valve	6
6	Acceleration valve	6
7	By pass valve	1
8, 9	Middle braking bulbs	1
10, 11	Rear braking bulbs	1
4, 12	Logical relationship “AND”	10

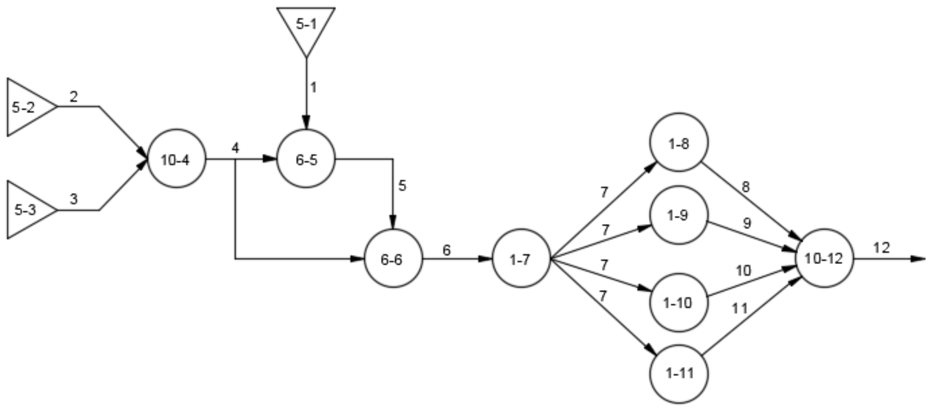


Figure 8. GO model for the middle and rear axle braking drive circuit of the braking system on a truck vehicle.

Data reliability of the system’s elements according to GO method

Survey timing options are the same as simple parallel systems. The results are shown in Table 5 as follows:

Table 5. Parameters to evaluate the reliability of the elements.

Order	Components	Failure intensity (damage/hour)	Maintenance intensity (times / hour)	Probability of working successfully
1	The impact of the driver	0	0	1
2	Compressed air tank 1	0.004	0.045	0.9822615
3	Compressed air tank 2	0.004	0.045	0.9822615
5	Hand braking reverse valve	0.001	0.02	0.9952535
6	Acceleration valve	0.003	0.012	0.9855486
7	By pass valve	0.003	0.012	0.9855486
8, 9	Middle braking bulbs	0.0032	0.014	0.9846686
10, 11	Rear braking bulbs	0.0032	0.014	0.9846686

According to the GO method, the system’s low reliability is determined through minimum cut sets by qualitative analysis. Using the MATLAB program to examine the system’s elements, we can determine the minimum cut sets as shown in Table 6.

Complex System

Selecting the front wheel brake drive circuit of the working brake system on the truck to research. The following assumptions are satisfied:

i. Consider the truck’s front wheel brake drive circuit working brake system as a stand-alone system, ignoring the guide branches, connections, and the relationship with other drive circuits [11].
ii. The structure of the 2-level braking valve and related hypotheses is determined according to the content presented in the ‘Simple serial system’ section.
iii. The probability of successful working of the pipes; the terminals are considered equal to 1.
iv. Only consider elements and systems in working or failed state
v. The minimum cut sets of the system are considered independent of each other.

Table 6. Results of GO qualitative analysis for the system.

Order	Element ID number	Broken elements	Probability of failure
1	1	The impact of the driver	0
	2	Compressed air tank 1	0.0177384
	4	Compressed air tank 2	0.0177384
	5	Hand braking reverse valve	0.0047465
	6	Acceleration valve	0.0144513
	7	By pass valve	0.0144513
	8	Middle braking bulbs	0.0153313
	9	Middle braking bulbs	0.0153313
	10	Rear braking bulbs	0.0153313
	11	Rear braking bulbs	0.0153313

Building GO model

Structure: The structure of the front-wheel braking drive circuit of the truck working brake system is shown in Figure 9. This circuit includes the following elements: Compressed air tank 2, 2-level braking valve cluster, valve pressure restriction 4, front ball brake bulbs 5 and 6. In which, the structure of the 2-level braking valve cluster includes: Compressed air tank 2, upper valve assembly, push the lever, lower valve assembly (including piston 15, seal 16, valve under 17, spring 19, seals 20, springs 26 - As shown in Figure 3).

System features: From the system analysis results, we can determine that in the review system using the redundant structure, with shared signals.

System interface: The input signal of the system is the driver's control effect. When the driver applies the brakes, the front wheels are filled with compressed air, which is the system's output signal.

Principle of working successfully: All brake bulbs are filled with compressed air when braking is performed.

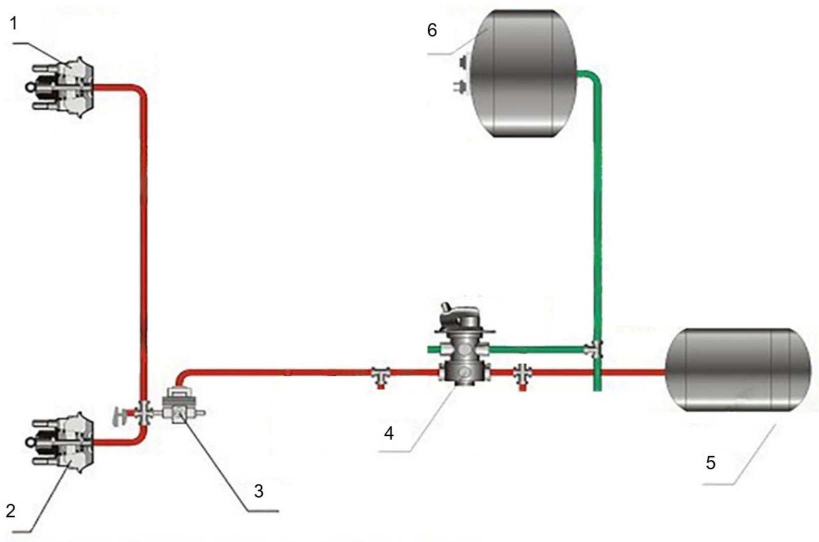


Figure 9. Structure of front wheel braking drive of working brake system on truck.

GO model set up

Based on the system analysis results above, the GO operators are selected as shown in Table 7, and the GO diagram is set up in Figure 10.

Table 7. Types of GO operators in the model

Order	Components	Type of GO operations
1	Control source cluster	5
2	Compressed air tank 1	5
3	Upper valve	6
5	Thrust 18	1
7	Compressed air tank 2	5
8	Under valve	6
9	Pressure limiter valve	1
10, 11	Front bulbs	1
4	Operating conditon of auxiliary group	20
6	Logical relationship of auxiliary structure	18A
12	Logical relationship "AND"	10

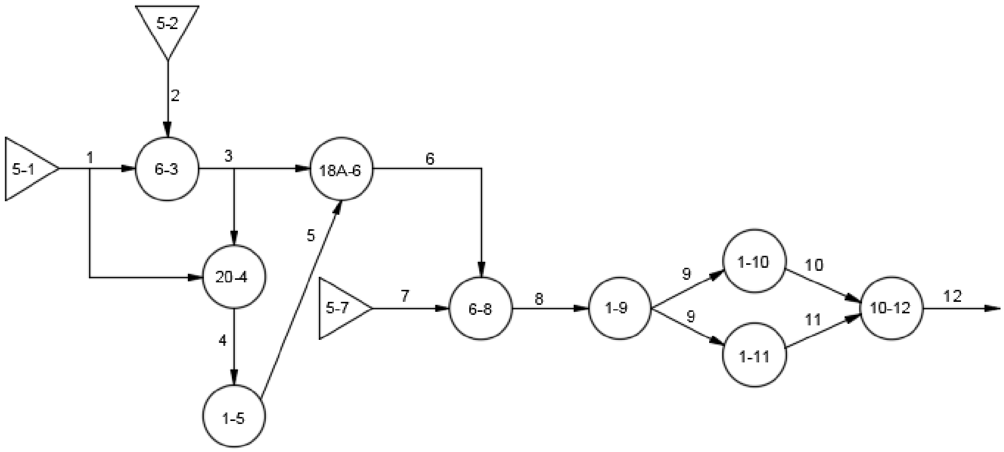


Figure 10. GO model for a front-wheel-drive circuit of the working braking system on a truck vehicle.

Data reliability of the system's elements according to GO method

Survey timing options are the same as for the simple parallel and series systems. The results are shown in Table 8 as follows:

Table 8. Parameters to evaluate the reliability of the elements.

Order	Components	Failure intensity (damage/hour)	Maintenance intensity (times / hour)	Probability of working successfully
1	Control source cluster	0.002	0.012	0.9903419
2	Compressed air tank 1	0.004	0.045	0.9822616
3	Upper valve	0.0012	0.008	0.9941359
5	Thrust 18	0.0008	0.0015	0.9960229
7	Compressed air tank 2	0.004	0.045	0.9822616
8	Under valve	0.0015	0.01	0.9927116
9	Pressure limiter valve	0.003	0.012	0.9855487
10, 11	Front bulbs	0.0032	0.014	0.9846687
1	Control source cluster	0.002	0.012	0.9903419

According to the GO method, the system's low-reliability components are determined through minimum cut sets by qualitative analysis. Using the MATLAB program to examine the system elements, we can determine the minimum cut sets as shown in Table 9.

Table 9. Results of GO qualitative analysis on the system

Order	Element ID number	Broken elements	Probability of failure
1	1	Control source cluster	0.0096580
	7	Compressed air tank 2	0.0177384
	8	Under valve	0.0072884
	9	Pressure limiter valve	0.0144513
	10	Front bulb	0.0153313
	11	Front bulb	0.0153313
2	2, 5	Compressed air tank 1, thrust 18	0.0000705
	3, 5	Under valve, thrust 18	0.0000233

CONCLUSION

The article introduces the method of analysis and determination of the low-reliable element of the multi-flows pneumatic braking system base on the GO methodology. In which the survey examples are selected from subsystems of the multi-flows pneumatic brake system on the trucks. From the initial structure diagram of the systems, we have established the GO model for the systems. Next, with data on each element's failure intensity and maintenance intensity, we continue to determine the reliability according to those elements' failure probability. Finally, based on a suitable GO algorithm and qualitative GO analysis process, we can identify elements, element clusters with low reliability with a serious impact on both systems work at different levels. Through specific examples, it shows that the GO analysis method is easy to implement, easy to survey, and test with the reliability model close to the system's real structure. Besides, probability formulas and algorithms are used for easy embedding and control in computer calculation programs. With GO method, we can ultimately determine the probability of working success of each element in the system and the whole system. All parts with a low probability of working success could also be identified, so special care should be taken during the operation and maintenance process that allows optimised maintenance, repair, and replacement spare-part planning. This is one of the points showing the applicability of the GO method to many different complex systems. The research's results can serve as the basis for other research on the reliability of other systems on a vehicle.

ACKNOWLEDGEMENT

Our research is sponsored by a project on Researching on Digital Transformation of Technical Assurance for Ground Vehicles According to the Life Cycle Product Management under the government program KC-4.0 /19-25.

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