International Journal of Latest Engineering Research and Applications (IJLERA) ISSN: 2455-7137

Volume – 07, Issue – 06, June 2022, PP – 01-08

Study the technical states of air compressed-hydraulic brake system by using a hidden Markov model

Giang-Nam.HOANG[1], Van-Dung.NGUYEN, Quoc-Bao.VU[1],
Nho-Bien.NGUYEN[1], Ngoc-Tuan.VU[1*]
[1]*Le Quy Don Technical University*

Abstract: In the using process, the technical state of the brake system is gradually changed in the deterioration trend. That significantly affects the reliability and working ability of the brake system and the truck.It is essential to determine the technical condition of the brake system. From there, propose solutions to improve the brake system's efficiency in the particular truck. The article suggests applying the hidden Markov model to study the change in the technical status of the air compressed-hydraulic brake system on a transport truck.The survey results show that the "most possible" states correspond to the failure of each component of the system. That helps answer the question: how will the brake system's ability to perform the functions change when corresponding to the change in the technical condition of the system components? Based on the technical status of the elements and the whole system, there will be a solution to exploit the equipment more effectively.

Keywords: Technical status; Brake system; Markov Model; Hidden Markov Model

1. Introduction

The technical condition of an engineering system can be determined scientifically by applying Markov's theory in considering the states and the possibility of transitions between them. This method is suitable for studying systems with many conditions. The article's content presents the results of applying the hidden Markov model to determine the technical status of the hydraulic brake system on transport cars. The structure of the paper is as follows: Part 1 presents the fundamental problems of Markov theory. In part 2, proceed to build a research model to change the technical status of the brake system. Part 3 examines changes in the technical state of the brake system, and part 4 deals with some issues of discussion.

2. Markov's theory

2.1. Markov Model

Consider a system described by the state space S = {1, 2,… N}. At any time t, the system can either transition from the Si state to one of the remaining N - 1 states or switch back to the S_i state itself. The transition probabilities a_{ij} characterizes the transitions between such states. Let q_t be the state the system reaches at time t. In the case of state transition probability a_{ij} independent of time t and independent of previously transitioned states, the system is Markov, and the process of the system is Markov process [1], [2]. We have:

$$a_{ij} = p\{q_{t+1} = S_j | q_t = S_i\}; \quad 1 \le i,j \le N \tag{1}$$

and satisfy the probability constraints:

$$a_{ij} \ge 0; \ \sum_{j=1}^{N} a_{ij} = 1 \tag{2}$$

The transition probabilities a_{ij} for all states in the system are described by the transition matrix A:

$$A = (a_{ij}) = \begin{bmatrix} a_{11} & \cdots & a_{1N} \\ \vdots & \ddots & \vdots \\ a_{N1} & \cdots & a_{NN} \end{bmatrix} \tag{3}$$

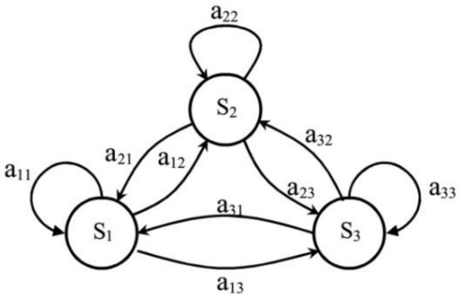
The initial probability of the S_i state (the probability that the system is in the S_i state at time t = 1).

$$\pi_i = p(q_1 = S_i), 1 \le i \le N \tag{4}$$

and satisfy the probability constraints:

$$\pi_i \ge 0; \ \sum_{i=1}^{N} \pi_i = 1 \tag{5}$$

The above stochastic process is called a Markov model. This model is observable because the output of the process is a set of states at each point in time, where each state corresponds to a physical event. Therefore, it is called the Existing Markov Model (Observable Markov Model – MM). The three-state Markov model is illustrated in Fig 1.



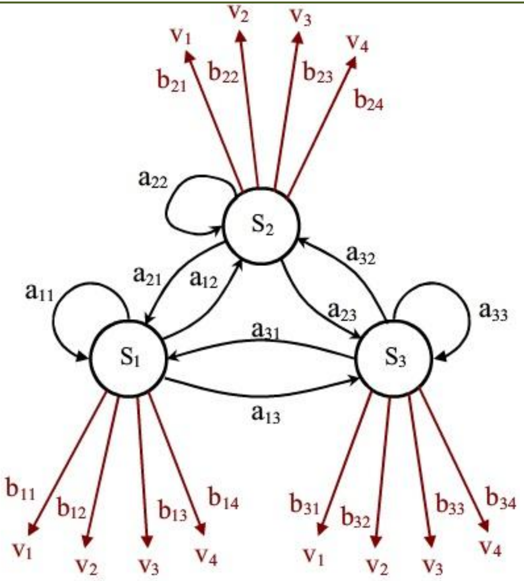


Figure 1: Three states Markov ModelFigure 2.Three states Hidden Markov ModelThe Markov model is characterized by:

- The number of states of the model, N.
- The state transition probability matrix, A = (a_{ij}), is determined by (1), (2) and (3).
- Initial distribution $\pi=\{\pi_1,\pi_2,\dots\pi_N\}$, determined according to (4) and (5).

2.2. Hidden Markov Model

The Markov model has certain limitations in solving some real-world problems. Because, in some cases, the states of the system are not observable or not fully observable. The Hidden Markov Model (HMM) is an extension of the Markov model [3], [4], [5]. In HMM, the observed events lie in each state and depend on the probability density function in those states. The system's states are not directly observable (it is hidden) but can only be observed through a set of other random processes that generate the sequence of observations.

Figure 2 illustrates a 3-state HMM with observable events in each state V = {v_1, v_2, v_3, v_4}. The probability (probability) of observing the event v_k in state S_j depends on the probability function of the observed events $b_j(k)$.

The hidden Markov model is characterized by:

- The number of states of the model, N.
- Number of distinct observable signals in each state, M. These observed signals are V = {v_1, v_2,…v_M} and the signal observed at time t is O_t.
- The state transition probability matrix, A = (a_{ij}), is determined according to (1), (2), and (3).
- The probability density functions of the observed signal in the state, B = ($b_j(k)$) with:

$$b_j(k) = p\{v_k = O_t | q_t = S_i\}; \quad 1 \le i, j \le N;\ 1 \le \mathrm{k} \le \mathrm{M} \tag{6}$$

and satisfy the probability constraints:

$$b_j(\mathrm{k}) \ge 0;\ \sum_{k=1}^{M} b_j(k) = 1 \tag{7}$$

- Initial distribution $\pi=\{\pi_1,\pi_2,\dots\pi_N\}$, determined according to (4) and (5).

For convenience of presentation, we convention that a set of parameters will represent each HMM: $\lambda=(A,B,\pi)$.

2.3. Three problems of HMM

For HMM, there are 3 fundamental problems [3], [4], [5].

Problem 1: Given the observed signal sequence O = {O_1, O_2,…, O_T} and HMM represented by the parameter set $\lambda=(A,B,\pi)$. We need to calculate $P(O|\lambda)$ – the probability of generating O from the model λ? It is called an evaluation problem. To solve this problem, use the forward-backward algorithm.

Problem 2: Given the observed signal sequence O = {O_1, O_2,…, O_T} and HMM represented by the parameter set $\lambda=(A,B,\pi)$. Find the most optimal series of states Q = {q_1, q_2, …, q_T} that generated O? This is a decoding problem. To solve this problem, use the Viterbi algorithm.

Problem 3: Given the observed signal sequence, $O = \{O_1, O_2,\dots, O_T\}$. Determine the parameters of the model $\lambda=(A,B,\pi)$ so that it maximizes $P(O|\lambda)$ – the probability of generating O from the model λ? It is called a model training problem. To solve this problem, use the Baum-Welch algorithm.

3. Building anHMM to study the change in technical characteristics of the hydraulic-pneumatic brake system

3.1. Structural characteristics of hydraulic-pneumatic brake system

The hydraulic-pneumatic brake system is equipped to transport heavy trucks with two separate brake lines for front and rear wheels. The hydraulic-pneumatic brake system is typical for work brake systems, engine brakes, and trailer brakes. The schematic diagram of the hydraulic-pneumatic brake drive is shown in Fig 3.

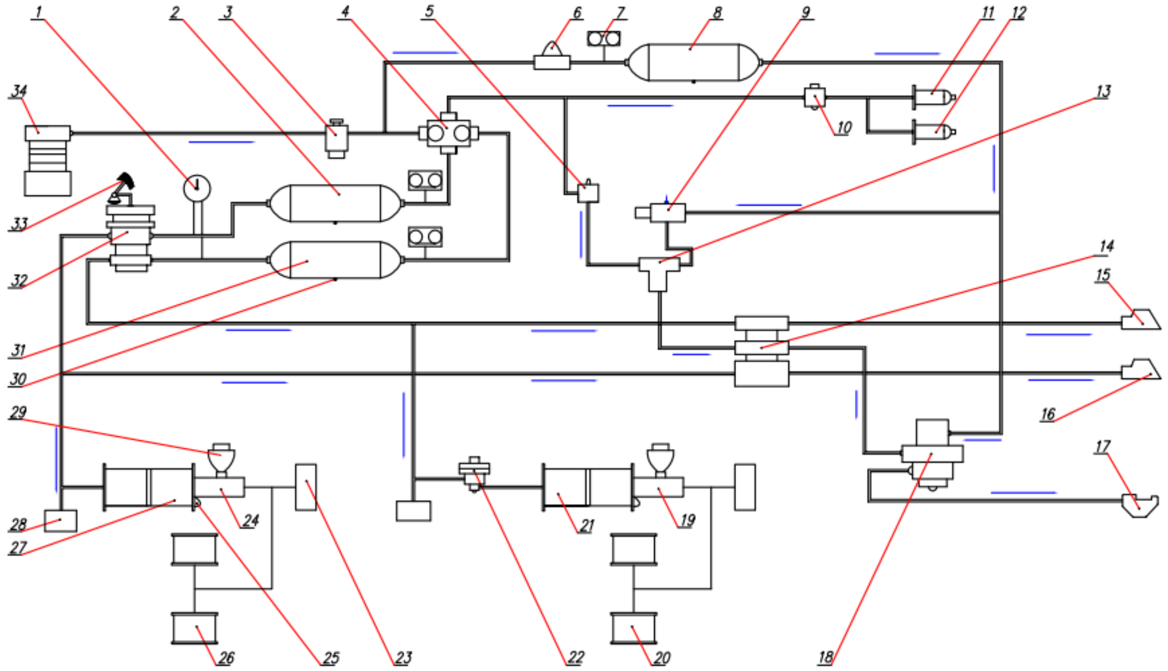


Figure 3. Diagram of the hydraulic-pneumatic brake system

1 – Pressure gauge; 2, 8, 31 – Compressed air tank; 3 – Dehumidifier and pressure regulator; 4 – 3-way protection valve; 5 – Pneumatic valve cuts trailer brake; 6 – One-way protection valve; 7 – Pressure sensor; 9 – Trailer stop brake control valve; 10 – Engine brake control valve; 11 – Pneumatic cylinder stops fueling; 12 – Pneumatic cylinder closes the exhaust valve; 13 – 2-way vent valve; 14 – 2-way trailer brake control valve; 15, 16 – Automatic connectors; 17 – "A" type connector; 18 – 1-way trailer brake control valve; 19, 24 – Master cylinder; 20 – Brake cylinder of rear wheel; 21, 27 – Pneumatic cylinders; 22 – Brake force regulator; 23 – The sensor turns on the brake signal; 25 – Brake system fault signal sensor; 26 – Brake cylinder of the front wheel; 28 – Check gas extraction valve; 29 – Oil tank; 30 – Drain valve for water sludge; 32 – Total brake valve; 33 – Brake pedal; 34 – Air compressor.

3.2. Building transition model of technical states

The brake system (Figure 3) consists of many elements with different functions. For simplicity, we only consider the working brake system with the following assumptions:

- The change of technical states of the brake system does not depend on time.
- The difference in the technical condition of the elements in the brake system is independent of each other.
- It only considers the following nine primary components: air compressor, pressure regulator, 3-way protection valve, force regulator brake, brake master valve, pneumatic cylinder, master cylinder, wheel brake cylinder, and brake pad. Each of the above elements will have different technical states during the whole working process of the system. The technical condition of these nine elements is divided into states: good, malfunction, and failure.
- State 1: Good is the state of the element when all its major and minor parameters conform to the specification.

- State 2: Malfunction is a state in which the element is damaged but still performs its function within the allowable limits.

- State 3: Broken is the state where the element cannot perform its function.

The other elements of the system are considered in good technical condition.

Through structural analysis and typical damage of HTP during exploitation, we divide the hydraulic-pneumatic brake system into the following technical states:

- S_0: good system status.
- S_1: system status of front-wheel brake drive failure.
- S_2: system status of rear-wheels brake drive malfunction.
- S_3: system failure status of a front-wheels brake drive.
- S_4: system failure status of a rear-wheels brake drive.
- S_5: System status of failure of both brake actuators of both axles.

From the above analysis, we build a transitional model of the technical states of the brake system (Figure 4). At any point in the mining process, the brake system will exist in one of the S_i states (i = 0, 1,…,5). Those are the hidden states of the model. The corresponding P_i probabilities characterize the system's probability in S_i states. The transition between states of the system is characterized by the corresponding state transition probabilities a_{ij} (i, j = 0, 1,…,5). At each S_i state of the brake system, each element of the system exists in one of the states: a good, malfunctioning, or failing. Those are the corresponding v_{kl} observations (k = 1, 2,…, 9; l = 1, 2, 3). The corresponding probability b_{kij} characterizes the probability of occurrence of each observation.

To determine the technical status of the brake system according to the built model, we proceed to solve three fundamental problems of HMM.

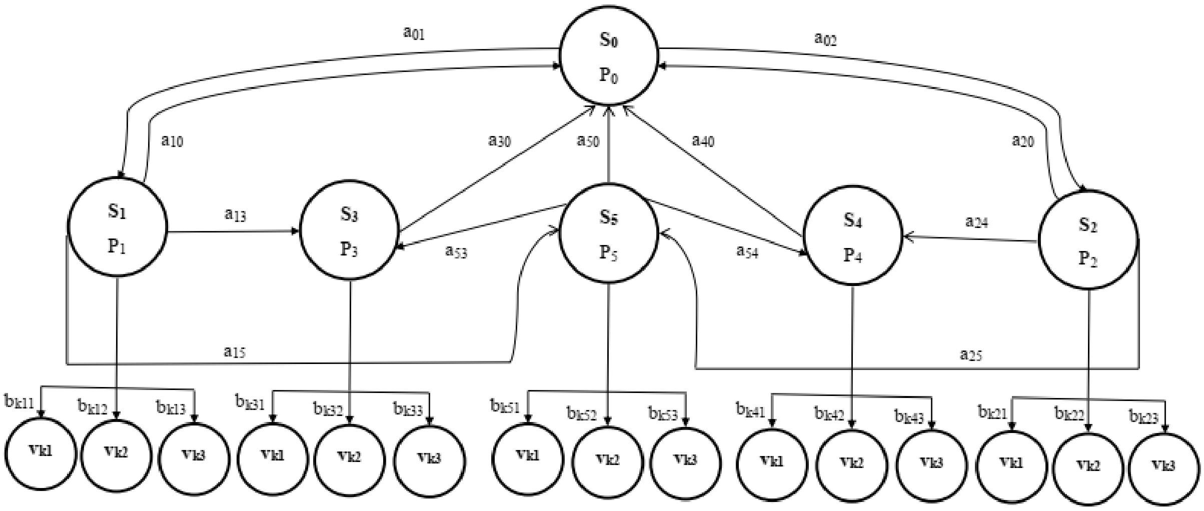


Figure 4.Transition model of technical states of Brake System

4. Application of HMM model Investigate changes in the technical status of hydraulic-pneumatic brake systems

4.1. Input parameters

To investigate the change in the technical condition of the brake system, we need to collect statistics on the damage to the brake system during the operation. The data is collected by statistical method and analyzing the vehicle operation records at the department, including truck activity monitoring book, vehicle repair records, and technical documents about brake system maintenance and repair. During operation, the brake system failure data are random quantities and should be processed to obtain the required information.

The survey parameters are the set of parameters $\lambda=(A,B,\pi)$ and the observation series O of the Hidden Markov Model.

Initial Distribution: $\prod = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$ (8)

State transition matrix:

A = [0 0,5 0,5 0 0 0; 0,5 0 0 0,2 0 0,3; 0,5 0 0 0 0,2 0,3; 1 0 0 0 0 0; 1 0 0 0 0 0; 0,8 0 0 0,1 0,1 0] (9)

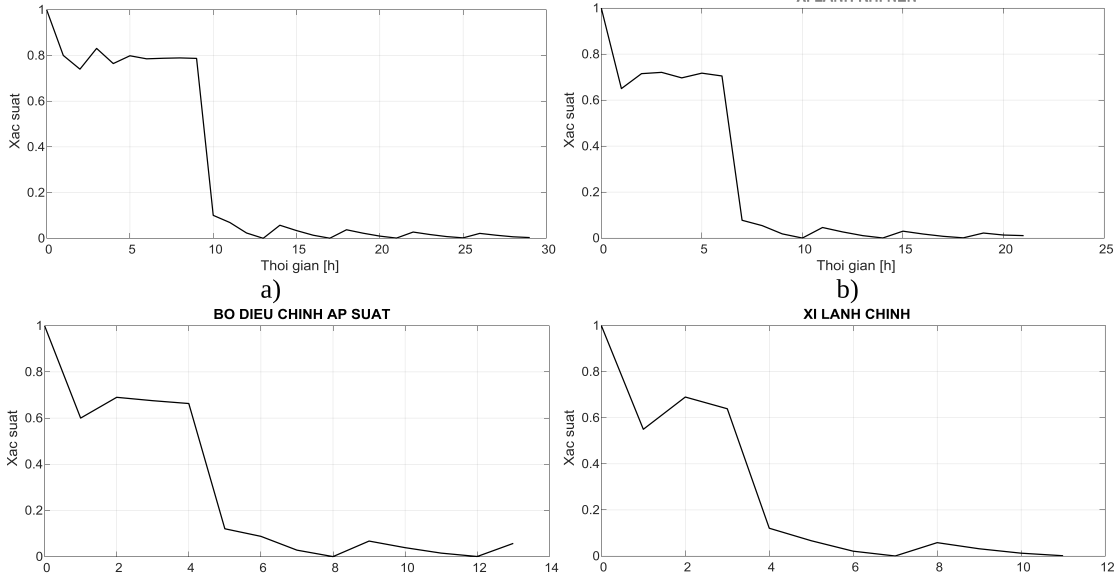
The observation matrix B and the observed series of damage O of the elements are listed in Table 1.

Table 1.The observation matrix B and the observed series of damage O

Component	**Observation matrix B**	**Observed series of damage O**
Compressor	B = [1 0 0; 0,8 0,15 0,05; 0,8 0,05 0,15; 0,3 0,3 0,4; 0,3 0,4 0,3; 0,6 0,2 0,2]	O = [1 1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 3] – 30observations.
Pressure regulator	B = [1 0 0; 0,6 0,2 0,2; 0,6 0,1 0,3; 0,2 0,3 0,5; 0,2 0,4 0,4; 0,5 0,2 0,3]	O = [1 1 1 1 1 2 2 2 2 2 2 2 2 3] – 14observations.
3-way protection valve	B = [1 0 0; 0,75 0,15 0,1; 0,75 0,05 0,2; 0,2 0,3 0,5; 0,2 0,35 0,45; 0,65 0,35 0,05]	O = [1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2 2 2 2 3] – 22observations.
Brake force regulator	B = [1 0 0; 0,7 0,25 0,05; 0,65 0,1 0,25; 0,4 0,1 0,5; 0,4 0,3 0,3; 0,6 0,2 0,2]	O = [1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2 2 2 2 3] – 22observations.
Main brake valve	B = [1 0 0; 0,7 0,16 0,14; 0,7 0,05 0,25; 0,1 0,2 0,7; 0,1 0,5 0,4; 0,5 0,3 0,2]	O = [1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2 2 2 2 3] – 22observations.
Pneumatic cylinder	B = [1 0 0; 0,65 0,16 0,19; 0,65 0,05 0,3; 0,25 0,2 0,55; 0,25 0,35 0,4; 0,55 0,3 0,15]	O = [1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2 2 2 2 3] – 22observations.
Master cylinder	B = [1 0 0; 0,55 0,2 0,25; 0,55 0,1 0,35; 0,2 0,2 0,6; 0,2 0,35 0,45; 0,5 0,2 0,3]	O = [1 1 1 1 2 2 2 2 2 2 2 3] – 12observations.
Wheel brake cylinder	B = [1 0 0; 0,5 0,25 0,25; 0,5 0,15 0,35; 0,1 0,2 0,7; 0,1 0,35 0,55; 0,45 0,15 0,4]	O = [1 1 1 1 2 2 2 2 2 2 2 3] – 12observations.
Brake pads	B = [1 0 0; 0,6 0,2 0,2; 0,6 0,1 0,3; 0,25 0,2 0,55; 0,25 0,35 0,4;0,55 0,15 0,3]	O = [1 1 1 1 1 1 2 2 2 2 2 2 2 2 3] – 15observations.

4.2. Survey results

The results of problem 1 (Fig 5) tell us the probability of observing the failure sequence of the components in the brake system. The likelihood of observing the series of observations corresponding to the good technical state of the element (observation 1) is the basis for evaluating the ability to work continuously without failure of the components in the system. The survey results show that the probability and continuous working time without damage of pneumatic elements are higher than that of hydraulic parts and brake pads. Thus, hydraulic components and brake pads occur more damage during operation than pneumatic elements.



a) b)

(c) (d)

Figure 5. Probability of observing the failure sequence of components in the brake system
a) Compressor; b) Pneumatic cylinder; c) Pressure regulator; d) Master cylinder

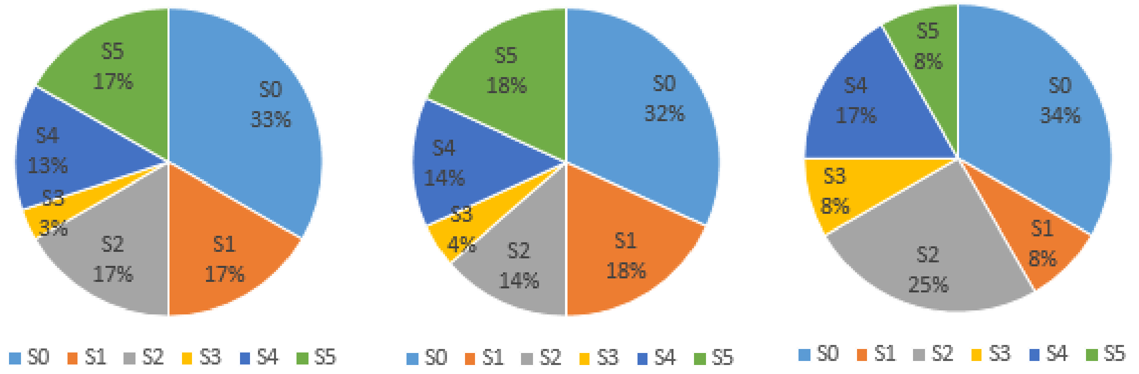
The results of problem 2 (table 2) tell us that the “most likely” state sequence generates the damaged lines of the elements. When a failure occurs to the brake system’s aspects, we know the system’s current state. In the brake system states, we need to pay more attention to the states S_3 and S_4. These are the states in which the brake system fails the brake drive lines of both axles. It is imperative to stop the vehicle from carrying out technical actions in these states.

From the statistical results in Table 2, we can see that the states S_3 and S_4 of the system correspond to the following part of the observed chain of failure of the elements. That means that the deterioration of the brake system's technical characteristics will become serious when the system is operated for a certain period. In the early stages of the service life, there are usually only failures that degrade the system's performance.

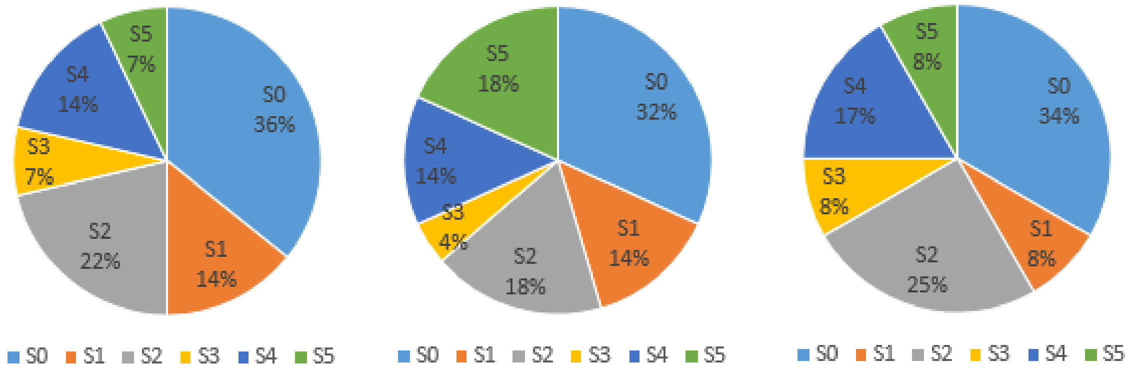
Table 2. States giving rise to a failure of components in the brake system

Time [10^3 km]	**Component/Observed series/States**																	
	Compressor		**Pressure regulator**		**3-way protection valve**		**Brake force regulator**		**Main brake valve**		**Pneumatic cylinder**		**Master cylinder**		**Wheel brake cylinder**		**Brake pads**	
	O	***S***	***O***	***S***	***O***	***S***	***O***	***S***	***O***	***S***	***O***	***S***	***O***	***S***	***O***	***S***	***O***	***S***
2,4	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0
4,8	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
7,2	1	0	1	0	1	0	1	0	1	0	1	0	1	5	1	5	1	5
9,6	1	2	1	2	1	2	1	2	1	2	1	2	1	0	1	0	1	0
12	1	0	1	0	1	0	1	5	1	0	1	0	2	2	2	2	1	2
14,4	1	2	2	1	1	2	1	0	1	2	1	2	2	4	2	4	2	0
16,8	1	0	2	5	1	0	1	2	1	0	1	0	2	0	2	0	2	1
19,2	1	2	2	4	2	2	2	0	2	2	2	2	2	2	2	2	2	5
21,6	1	0	2	0	2	5	2	1	2	5	2	5	2	4	2	4	2	4
24	1	2	2	2	2	4	2	5	2	4	2	4	2	0	2	0	2	0
26,4	2	0	2	4	2	0	2	4	2	0	2	0	2	1		1	2	2
28,8	2	1	2	0	2	1	2	0	2	1	2	1	3	3	3	3	2	4
31,2	2	5	2	1	2	5	2	1	2	5	2	5					2	0
33,6	2	4	3	3	2	4	2	5	2	4	2	4					2	1
36	2	0			2	0	2	4	2	0	2	0					3	3
38,4	2	1			2	1	2	0	2	1	2	1						
40,8	2	5			2	5	2	1	2	5	2	5						
43,2	2	4			2	4	2	5	2	4	2	4						
45,6	2	0			2	0	2	4	2	0	2	0						
48	2	1			2	1	2	0	2	1	2	1						
50,4	2	5			2	5	2	1	2	5	2	5						
52,8	2	4			3	3	3	3	3	3	3	3						
55,2	2	0																
57,6	2	1																
60	2	5																
62,4	2	4																
64,8	2	0																
67,2	2	1																
69,6	2	5																
72	3	3																

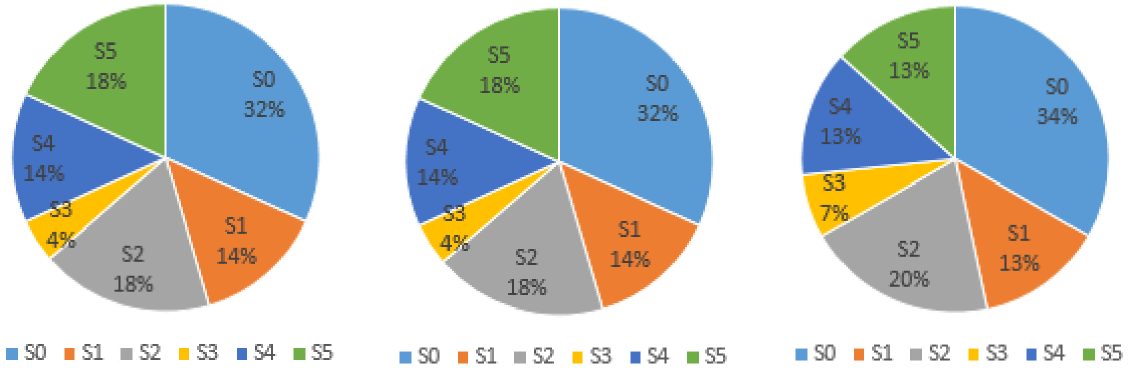
Fig 5 shows the percentage of S_i states of the brake system corresponding to each failure sequence of the elements. From the graph, we see that the number of S_2 states is more than the number of S_1 states; the number of S_4 states is more than the number of S_3 states. The rear-wheel brake drive will have more damage than the front-wheel brake drive during operation.



Compressor Brake force regulator Master cylinder



Pressure regulator Main brake valve Wheel brake cylinder



3-way protection valve Pneumatic cylinder Brake pads

Figure 5. Statistics of S_i states corresponding to the failure observations of the components

Statistical results in Table 2 show the times when the HTP is “most likely” to fail the brake drive of the bridges. During the operation, at the above points, it is necessary to pay attention to check for damage that may lead to the loss of the working capacity of the brake drive lines. The survey results also show that damage to the wheel brake cylinders and master cylinders is likely to lead to the fastest brake failure (14,400 km), corresponding to the 2nd maintenance time (13,000 - 15,000 km).From the results of problem 2, we can determine the critical work contents that need to be performed when performing maintenance and repair of HTP at a specific time. The content of maintenance and repair for the components whose damage at that time is “most likely” to lead to failure of the brake drive of the bridges will need to be paid more attention than other elements. For example, at 14,400 km, it is necessary to focus on checking the wheel brake cylinder and master cylinder; at the time of 19,200 km needs to focus on checking the pressure regulator. Carrying out the maintenance and repair of the brake system with such a focus will help reduce costs and improve equipment operation efficiency.

5. Conclusions and Perspectives

This paper presents the application of HMM to study the change in the technical status of the hydraulic-pneumatic brake system on transport cars. The survey results have evaluated the ability to work continuously without damage to the components in the brake system. At the same time, assess the ability to perform the functions of the brake system when the failure of system components occurs. The survey results also identify when the system is “most likely” to fail the brake drive lines and identify the element that needs to be a “priority” for technical action to avoid occurrence damage resulting in inoperability of the brake system. That is the basis for solutions to improve the quality of equipment exploitation. When we know the change in the technical condition of the brake system during the operation, we need to take measures to optimize the exploitation activities for the best equipment exploitation efficiency.

Problem 3 will give us the parameters $\lambda=(A,B,\pi)$ of the model so that the probability of observing the failure sequence of the element is the highest. It is the basis for adjusting vehicle operations to maintain the brake system’s technical condition in the most optimal state, and it is the next development direction of the paper. Currently, the forms for monitoring and registering vehicle operations at the unit do not meet the requirements of providing complete and accurate data to survey the change in the technical status of the brake system utilizing HMM application method. Therefore, it is necessary to have appropriate solutions to collect vehicle exploitation data for more accurate research results. The forms need to detail the damage statistics of the components in the brake system. The article results will contribute to the basis for applying Markov’s theory to study the technical status of other clusters and systems in automobiles.

References

[1] GS.TSKH. Kuravsky L.S, TSKH. Nguyễn Quang Thường (2016), Mô hình Markov ứng dụng trong chẩn đoán và dự báo, NXB Khoa học và Kỹ thuật, Hà Nội.

[2] Nguyễn Duy Tiến (2000), Các mô hình xác suất và ứng dụng, NXB ĐHQG Hà Nội, Hà Nội.

[3] Przemyslaw Dymarski; “Hidden Markov Models”, Theory and Applications, InTech (2011),Warsaw University of Technology, DOI: 10.5772/601

[4] Department of Computer Science (2018), “A Revealing Introduction to Hidden Markov Models”, San Jose State University, April 12, 2021

[5] Lawrence R. Rabiner (1989), “A tutorial on Hidden Markov models and selected applications in speech recognition”, IEEE.

[6] Li Ling-yi, Wang Deng-jiang, Zhou Tao-tao, Tang Ting, Sun Hai (2011), “Reliability Prediction and Markov Analysis of Braking System based on Relex 2009”, IEEE.

[7] Xin Liu, Yunxian Jia, Jie Zhou, Zewen He, Yingbo Zhang (2016), “The Dynamic Fault Tree Analysis Method Based on Fuzzy Markov Process and Its Application”, 2nd Information Technology and Mechatronics Engineering Conference (ITOEC 2016).

[8] Jacek Rudnicki (2015), “Application Isssues of the semi-Markov Reliability model”, Polish Maritime Research, No 1/2015.