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DISC BRAKE FAILURE ANALYSIS OF THE MOTOR VEHICLE BRAKING SYSTEM

ABSTRACT: The braking system of motor vehicles holds paramount importance for their active safety in traffic. Disc brakes, being the executive components of the braking system, are the most critical units in terms of reliability and safety of operation due to their operational conditions. It is crucial to analyse all potential failure modes of disc brake components and ascertain their causes and consequences. The Fault Tree Analysis (FTA) method was used for the qualitative analysis of disc brake component failures. FTA is a deductive method that establishes connections between the top-level failure event of the object under consideration and the basic failure events of its constituent elements. The fault tree of the disc brake was developed based on a detailed analysis of the object's structure, the functioning of individual elements, operational conditions, a failure data during exploitation, and other pertinent information. The developed fault tree forms the foundation for conducting reliability and safety analyses of a quantitative nature. The conclusion underscores the significance of applying reliability theory methods and discusses the potential applications of the obtained results.

KEYWORDS: motor vehicles, disc brakes, Fault Tree Analysis (FTA)

INTRODUCTION

A significant part of automotive technology relates to braking [5]. The ability to decelerate a vehicle is one of the primary requirement of preventive safety. Among other things, the braking systems of modern motor vehicles must meet numerous quality requirements imposed by legal obligations from the standpoint of traffic safety. Accordingly, braking systems consist of service, auxiliary, parking, and, in the case of heavier commercial motor vehicles, supplemental brakes. Each subsystem of the braking system includes a control mechanism, transmission mechanism, and brake. Brakes are the executive components of the braking subsystems through which their tasks are executed. Therefore, their importance within the braking system is particularly emphasized. Two basic types of brakes are used in motor vehicles: drum brakes and disc brakes. In the case of disc brakes, the friction surface is oriented perpendicularly to the axis of the disc rotation, and pressure is applied to it in an axial direction. This is why disc brakes are also called axial brakes. Due to their good characteristics, primarily in terms of performance and reliability, disc brakes are used on both the front and rear axles of modern passenger cars and the front wheels of commercial vehicles. The goal of this paper is to provide a detailed analysis of the failure modes of disc brake components and their causes.

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For the analysis of failures in technical system components, Fault Tree Analysis (FTA) is most commonly used. The basis of fault tree analysis involves translating physical systems into structural logical diagrams. FTA was developed in the early 1960s in the United States by H. A. Watson for the analysis of the safety of rocket launch systems, specifically for the U.S. Air Force [1, 4]. FTA is conducted according to a specific methodology, using symbols for events, logic gates, and transfer of fault tree sections [2, 3]. This method is particularly suitable for analysing the reliability and safety of systems whose failures could lead to severe consequences for people and the environment.

DISC BRAKE STRUCTURE AND FUNCTIONING

In Figure 1 [7], the components of the considered disc brake model for motor vehicle braking systems are shown. The study explains the role of similar components in disc brakes with a comparable design solution [6]. The basic parts of a disc brake are the disc, brake pads, and calliper. The disc is a rotating element mounted on the wheel hub and fastened with bolts. Cast iron is most commonly used for manufacturing the disc. Additionally, depending on the application conditions and vehicle types, discs can be made from steel, ceramic materials, or aluminium. For better heat dissipation, various disc designs include holes, ventilation openings, or grooves. Brake pads consist of a metal backing and a lining made of friction material. The lining materials can be organic (a mixture of rubber resin, glass, and other substances), semi-metallic (copper, graphite, and steel), or ceramic. The efficiency of disc brakes largely depends on the materials used for the disc and the lining. The brake calliper encompasses the disc from both sides, which is why it is often called a clamp. Inside the calliper, on both sides of the disc, are the brake pads. The brake cylinder is located within the calliper body. Although the brake cylinder is inside the disc brake calliper, it is part of the hydraulic transmission system used to activate the disc brake. Depending on the design, the calliper can be floating (with one brake cylinder) or fixed (with brake cylinders on both sides of the disc). The calliper bracket is attached to the stationary part of the wheel hub. An important element for protecting disc brake components from external environmental influences is the protective plate, which is mounted on the wheel hub on the inner side of the disc brake.

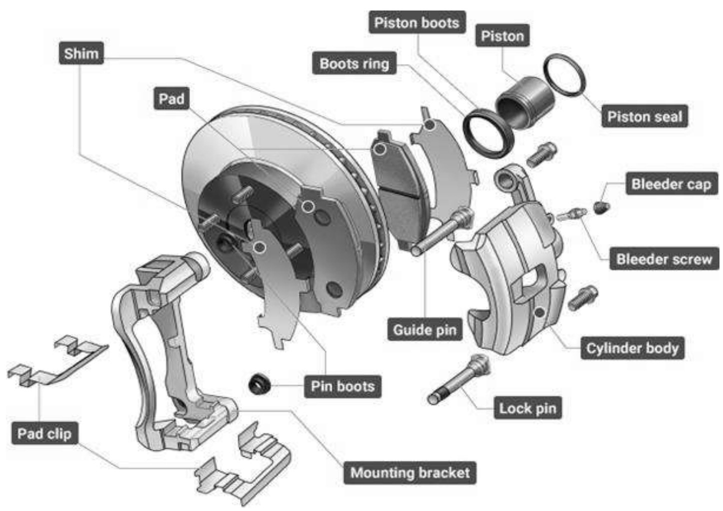

Figure 1 Parts of a Disc Brake

The considered disc brake model functions as follows. When the brake pedal is pressed, brake fluid under high pressure from the master cylinder is delivered to the brake cylinder at the wheel through metal and flexible hoses. The high pressure of the fluid in the brake cylinder moves the piston, which presses the metal part of the inner brake pad and forces the friction lining against the surface of the disc. After that, the calliper moves away from the disc in an axial direction, pulling the outer brake pad with it. Axial pressure from the pad linings on the disc surface creates friction, which slows the rotation of the disc, and therefore the vehicle's wheel. In this way, the vehicle's kinetic energy is converted into thermal energy in the friction elements of the brakes and dissipates into the surrounding air. When the brake is released, the disc brake components return to their initial position, allowing the disc to rotate freely.

THE FAULT TREE FOR DISC BRAKE FORMING AND ANALYSIS

To better understand the disc brake system for motor vehicles from the perspective of failure occurrences, the Fault Tree Analysis method has been applied to form the fault tree for the examined object. A combined approach was used in this process. Some of the intermediate events in the fault tree are failures of disc brake components, while others are defined through operational parameters. For creating the fault tree, symbols for top or intermediate events (rectangles), primary basic events (rectangles with a circle below), secondary basic events (rectangles with a diamond below), and logical gates OR are used [2]. Under the top event "Disc Brake Failure," in the fault tree shown in Figure 2, both complete and partial brake failures are considered. Complete failures occur when no braking torque can be achieved, and these are rare. In the case of partial failures, the operational characteristics of the disc brake (such as braking intensity, heat dissipation capability, smooth operation without vibrations on the brake pedal and steering wheel, noise level during braking, response speed of the brake upon activation, etc.) are significantly degraded.

Failures that lead to a reduction in braking torque are commonly referred to as friction failures. These can be either temporary or permanent. Temporary friction failures can occur due to the presence of water on the friction surfaces of the disc and brake pads or due to overheating of the friction surfaces during prolonged braking, while driving downhill or frequent use of the brakes. The presence of water on the friction surfaces of the disc brake reduces the coefficient of friction and the achieved braking torque. During braking, the heating of the brake elements causes the water to evaporate, restoring the brake's operational capability. Additionally, it should be noted that in disc brakes, centrifugal force quickly removes water from the friction surfaces as the vehicle moves. In cases of prolonged braking, the heat generated by converting the vehicle's kinetic energy exceeds the thermal energy dissipated by the brake components to the environment. This results in a high operating temperature for all elements of the disc brake. The high operating temperature affects the reduction in the coefficient of friction between the disc and the pad linings. The phenomenon of reduced friction properties due to increased temperature is known as "fading" [5]. This phenomenon is particularly pronounced in brakes where the non-metallic part is made of asbestos. Cooling the friction linings, or returning them to moderate operating temperatures, restores the friction properties and leads to the "recovery" of the coefficient of friction. Therefore, these and similar types of malfunctions are referred to as temporary failures.

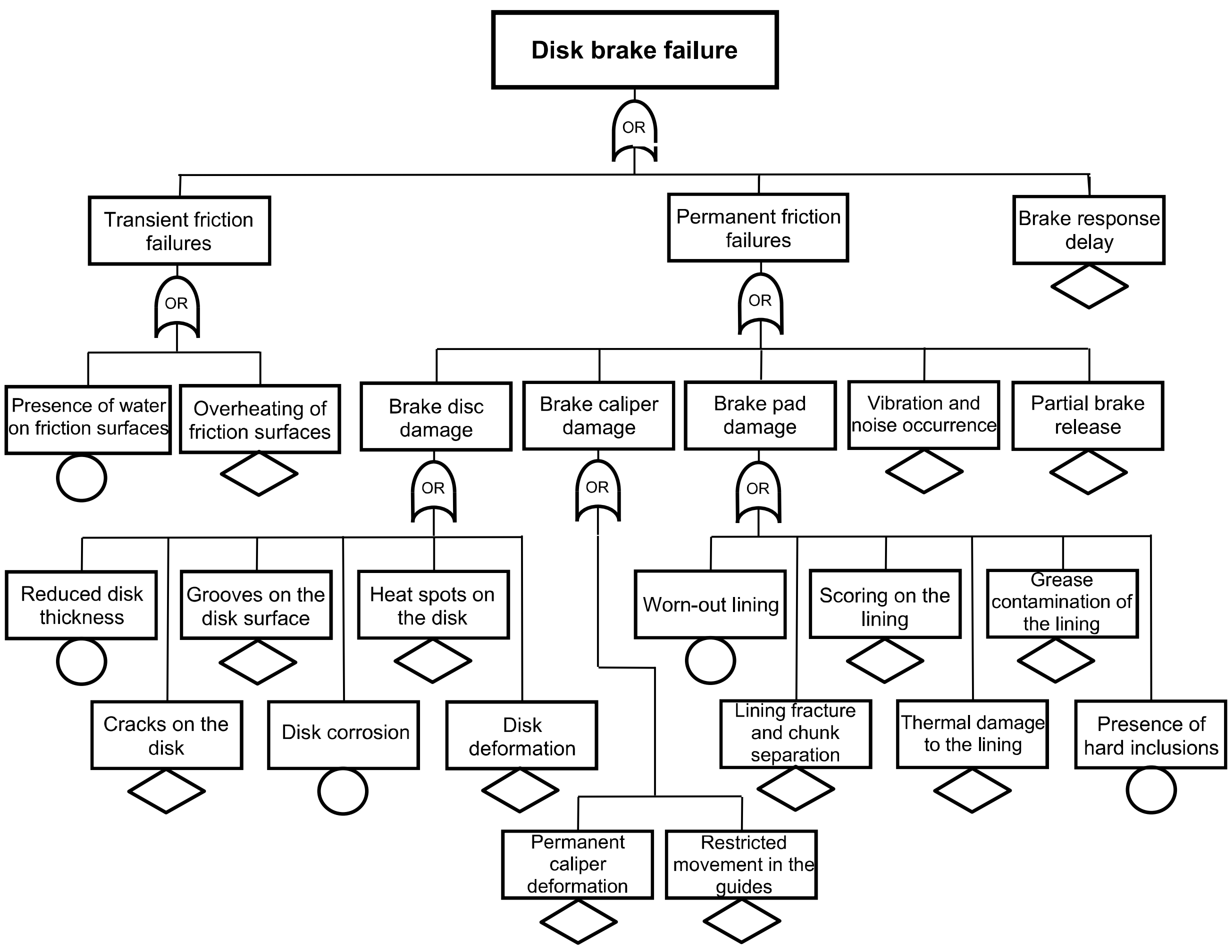

Figure 2 Disc Brake Fault Tree

Permanent friction failures can occur due to damage to specific components of the disc brake system, which is manifested by a reduction in braking torque, the generation of vibrations and noise, and incomplete release when the brake is not activated.

In Figure 3, the most common types of damage to brake discs that occur during operation are shown [8]. These include reduced disc thickness, the formation of cracks on the disc, deep grooves on the disc, disc corrosion, thermal spots on the disc, and disc deformation. All these damages typically lead to the replacement of the disc.

For some types of damage, if they are less severe, it may be possible to correct the defects through machining, albeit with a deliberate reduction in the disc thickness. However, this can only be done up to the minimum allowable disc thickness.

Over time, under normal operating conditions, friction leads to the wear of the friction surfaces of the disc and pads. This results in a reduction in the thickness of the disc and pads. Additionally, issues such as surface wear and roughness of the disc, corrosion deposits, disc surface unevenness, non-parallelism, thickness variations, and disc deformation require machining to correct the identified defects. This process significantly reduces the disc's thickness. Figure 3 a) shows a comparative view of a new and worn disc. Each disc is stamped by the manufacturer with the thickness of the new disc and the minimum allowable thickness, after which replacement is mandatory. Thinner discs dissipate heat less effectively to the external environment and therefore heat up more. Reducing the disc thickness decreases the static strength of the material and can lead to the formation of cracks (Figure 3 b). Cracks on the disc are radial and always occur perpendicular to the direction of pad movement. They are detected through visual inspection. Larger cracks necessitate disc replacement, while smaller cracks may be tolerated.

Due to prolonged heating of the friction elements, the hardness of the sliding surfaces of the brake disc decreases, making it more susceptible to abrasive wear when in contact with hard inclusions in the brake pads. This results in a significant increase in wear intensity and the formation of deep grooves (ridges) on the disc surface (Figure 3 c)). If the depth of the grooves is so great that it cannot be eliminated through machining within the allowable disc thickness limits, this part must be replaced with a new one.

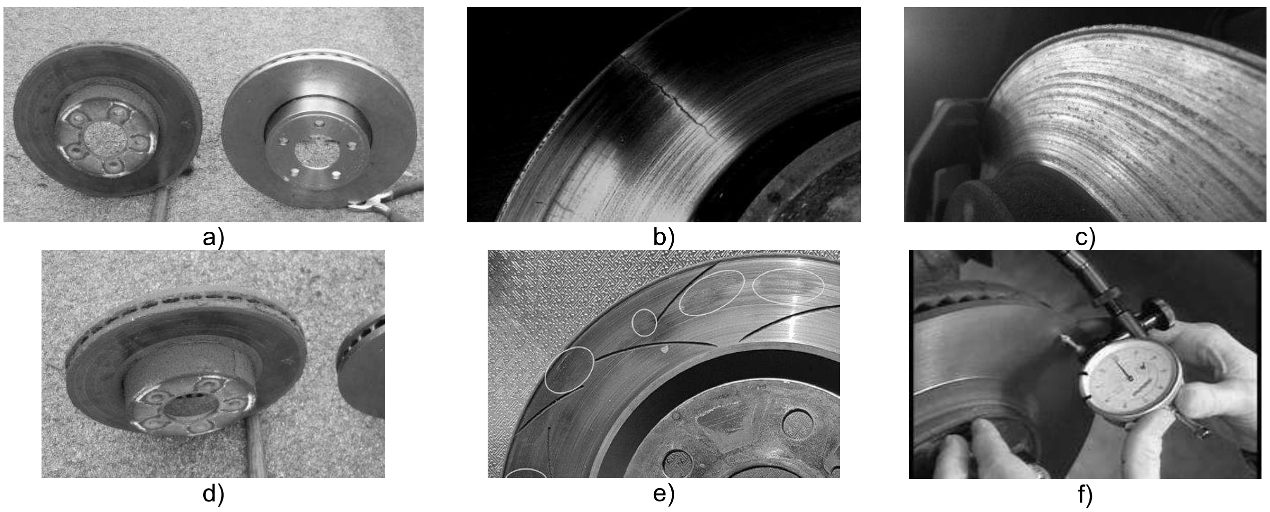

Figure 3 Different forms of disc damage: a) Worn and new disc, b) Crack on the disc, c) Grooves caused by reduced hardness of the disc material, d) Corrosion of the disc, e) Thermal spots on the disc, f) Deformation of the disc

During the operation of disc brakes, exposure to external elements (such as water, humidity from the air, road salt, etc.) leads to corrosion of brake discs made of iron (Figure 3 d)). Thin layers of corrosion are removed during braking and do not affect brake efficiency. However, if the vehicle is not used for an extended period, the thickness of the corroded layer can become significantly greater, potentially leading to permanent damage to the disc. Due to uneven heating of the disc surfaces with and without the corrosive layer, permanent deformations (warping) of the disc can occur. This results in a significant reduction in braking torque and causes brake pulsation.

Thermal spots on the sliding surfaces of the disc occur due to the formation of cementite in certain areas of the disc surface (Figure 3 e)). Due to its hardness, this leads to intense local heating when in contact with the brake pads, resulting in plastic deformations of the disc. Thermal spots are raised areas on the disc surface that reduce braking torque and cause vibrations during braking. If the thermal spots are large, disc replacement is necessary.

Disc deformation occurs due to intense local heating and uneven cooling. If the disc experiences rapid cooling when in contact with water, residual stresses may develop. Depending on the intensity of these stresses, this can lead to cracks or permanent deformations of the disc plate. Figure 3 f) illustrates how measuring the deviation of the disc surface from its plane of rotation determines the extent of deformation.

Figure 4 [7, 9, 10] shows various forms of brake pad damage. Depending on the design of the disc brake, the quality of the component materials, driving and braking conditions, and environmental factors, different types of damage to the brake pads can occur. Due to the lower hardness of the material, the pad linings are significantly more exposed to wear than the disc. Figure 4 a) provides a comparative view of a new and worn brake pad. If the pads are not replaced on time and the linings are completely worn out, in addition to a drastic reduction in braking torque, there will be squealing during braking and significant damage to the brake disc due to metal-to-metal contact. An important characteristic of all friction materials used for linings is the wear intensity. This property determines the durability or lifespan of the friction lining, as well as the frequency of preventive inspections before the pads need to be replaced. Damage to the sliding surfaces of the brake disc can significantly increase the wear of the linings. Wear of the pads and disc generates dust, which, if the seal of the brake cylinder is damaged, can reach the sliding surfaces of the cylinder and piston, worsening the friction conditions. In extreme cases, this can lead to piston seizing. Cracking and disintegration of pad fragments (Figure 4 b) lead to a significant deterioration in the braking performance. Pieces of the lining can be caught by the disc and get lodged between the lining and the disc, causing braking of the wheel even when the brake is not activated, which is particularly dangerous for traffic safety. Additionally, it can result in deep grooves on the friction surface of the disc.

Causes of uneven wear of brake pad linings (Figure 4 c) can include improper installation of the brake pad or calliper, deformation of the calliper, improper installation or deformation of the disc, various forms of damage to the disc's sliding surfaces, etc. After identifying the damage to the lining, the first step is to determine and address the root cause. Depending on the extent of the damage, the pad lining should either be resurfaced or replaced with a new one.

Prolonged high operating temperatures of the disc brake components can lead to thermal overloading and burning of the brake pad material (Figure 4 d). In this case, the binder material of the lining is destroyed, causing the lining to crumble. The surface of the lining becomes porous. The ability to generate braking torque is lost, and replacing the damaged pads is necessary. This is an example of a failure mode that leads to complete failure of the disc brake.

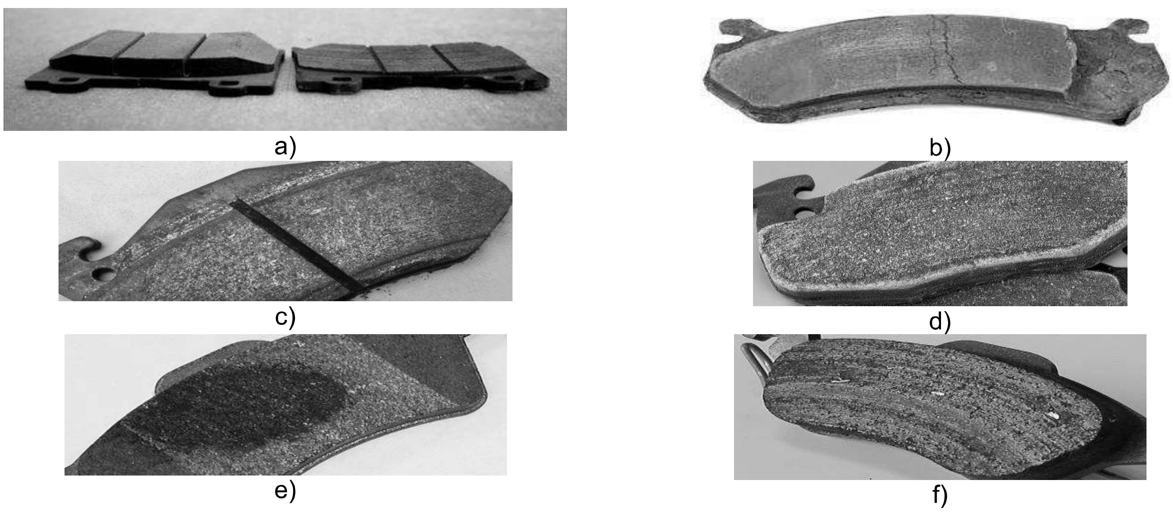

Figure 4 Different forms of brake pad damage: a) New and worn pad, b) Cracking and disintegration of pad fragments, c) Uneven wear of the pad surface, d) Thermally permanently damaged lining, e) Greasing of the pad's sliding surface, f) Presence of hard inclusions in the lining

Greasing of the pad's sliding surface with oil or grease from external sources, or oil leakage from the brake cylinder due to inadequate sealing, leads to contamination of the lining and a reduction in the coefficient of friction (Figure 4 e). Additionally, during brake operation, a layer of soot forms on the friction lining, which has properties significantly different from the base friction material. This greatly reduces the coefficient of friction of the brake linings. In cases of contamination or soot build up, restoring the brake's performance involves cleaning the brake disc and resurfacing the friction surfaces of the pads. If contamination is caused by oil leakage from the brake cylinder, it is necessary to replace the cylinder's sealing rings.

One of the fundamental properties of brake shoe linings is the material homogeneity and the percentage of undesirable inclusions. The presence of hard inclusions in brake pad linings not only reduces the coefficient of friction between the linings and the disc but also causes abrasive wear on the disc's friction surface. As a result, the disc surface becomes scored, and braking torque decreases. Hard inclusions can become embedded in the surface layer of the lining during operation. If, during intense wear, metal particles from the disc separate and come into contact with the lining, they can be pressed into the lining's surface due to the high contact pressure (Figure 3 f).

The reliability and service life of disc brakes largely depend on the uniformity of wear on the friction elements. The wear of the brake linings is proportional to the surface pressure. Uniform distribution of surface pressure on the friction surfaces of the pads affects even wear of the disc and pads, achieving maximum braking performance, and generating lower operating temperatures on the contact surfaces. The law of surface pressure distribution on the pads depends on several factors, primarily the design of the disc brake, the rigidity of the disc, pads, and linings, the way the pads are supported, the shape of the contact surfaces of the pads and disc, etc.

High operating temperatures in disc brakes can reduce the strength of the calliper material. Under high loads, this can lead to permanent deformations. Deformation or improper installation and positioning of the calliper and disc can result in asymmetric wear of the disc, necessitating its replacement. Corrosion and the accumulation of dirt can also cause difficulty in the movement of the calliper along its guide rails. Therefore, regular cleaning and lubrication of the calliper guides and mounts are essential.

The occurrence of vibrations in the brake pedal and steering wheel, along with noise during operation, represents a particular type of permanent friction failure in disc brakes. Lateral run out of the disc during braking causes periodic movement of the brake pads towards and away from the disc, leading to periodic motion of the brake calliper piston. Changes in pressure within the hydraulic system result in pulsation of the brake pedal and vibrations in the steering wheel. Similar effects can be caused by uneven disc thickness and non-parallelism, elevated zones on the disc's sliding surfaces (such as thermal spots or corrosion deposits), improper installation of the disc, brake calliper, or pads, and other factors.

When it comes to incomplete release, unlike drum brakes where return springs push the brake cylinder pistons back to their initial position, disc brakes do not have such springs. Even the slightest resistance to the movement of the piston can have undesirable consequences, such as continuous contact between the sliding surfaces of the disc and the brake pads. This results in constant braking of the vehicle and unnecessary wear of the friction elements. The piston movement can be hindered due to issues like piston seizing or difficult movement of the calliper along its guides. Additionally, improper installation of the disc, calliper, and pads, excessive lateral run out of the disc, inadequate disc or pad thickness, and other factors can lead to continuous braking of the disc.

The causes of delayed response in disc brakes can be due to changes in the disc brake components or various failures in the braking command or hydraulic transmission mechanism. When it comes to the disc brake components, reduced thickness of the disc and brake pads requires a longer stroke of the hydraulic cylinder piston and a greater volume of brake fluid in the cylinder, leading to a delay in response. Additionally, difficulties in the movement of the floating calliper along its guides and hindered piston movement in the cylinder also increase the brake response time.

CONCLUSIONS

By forming a fault tree for the disc brake system of a motor vehicle, a detailed analysis of potential failure modes of its components and their causes has been conducted. The results of this analysis can be used for developing solutions to address identified deficiencies, creating user manuals, diagnosing failures, and preparing maintenance instructions and planning maintenance measures during operation. When forming the fault tree, it was assumed that the quality of the components complies with the design documentation and that the brake elements were assembled correctly. Additionally, it is assumed that the braking system maintenance is performed by qualified personnel using original spare parts. In further work on evaluating the reliability of disc brakes, critical components that limit the reliable and safe operation of the braking system as a whole can be identified. Comparative analysis of the fault tree for different designs of disc brakes and various materials for the brake disc and brake shoe linings can be used to select the optimal solution for specific usage conditions. Additionally, future work can include an analysis of the impact of the human factor, in terms of operating conditions and maintenance practices, on the reliability and service life of the disc brake.

REFERENCES

[1] Bertsche B.: Reliability in automotive and mechanica lengineering, VDI-Buch, Springer-Verlag, Berlin Heidelberg, 2008.
[2] Ćatić D., Gašić M., Savković M., Glišović J.: Fault tree analysis of hydraulic power-steering system, International Journal of Vehicle Design, Inderscience Publishers, United Kingdom, 2014, Vol. 64, No 1, pp. 26-45.
[3] Ćatić D., Glišović J., Miković J., Veličković S.: Analysis of failure causes and the criticality degree of elements of motor vehicle's drum brakes, Tribology in Industry, 2014, Vol. 36, No. 3, pp. 316-325, ISSN 0354-8996.
[4] Ericson C.: Fault Tree Analysis – A History, in: Proceeding of the 17th International system Safety Conference, 1999, http://www.fault-tree.net/papers/ericson-fta-history.pdf. Accessed on: 17.01.2010.
[5] Todorović J. :Kočenje motornih vozila, Zavod za udžbenike i nastavna sredstva, Beograd, 1988., 406 s.
[6] Vasiljević S., Ćatić D., Glišović J., Fault tree analysis of motor vehicle's disc brake, Tractors and power machines, Vol. 24, No. 1/2 pp. 72-81, Novi Sad, Dec. 2019.
[7] Web page: https://www.ingenieriaymecanicaautomotriz.com/disc-brakes-construction-working-principle-types-and-rotor-materials/, Accessed on: 15. 06. 2024.
[8] Web page: https://mzwmotor.com/brake-rotor-guide/#c4, Accessed on: 15. 06. 2024.
[9] Web page: https://www.autoexclusive.rs/vesti/interesantno/kako-da-proverite-kocione-plocice-na-automobilu, Accessed on: 15. 06. 2024.
[10] Web page: https://www.knowyourparts.com/technical-resources/brakes-and-brake-components/the-danger-of-delaminated-brake-pads/, Accessed on: 15. 06. 2024.