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Design and Simulation of Alternate of Pneumatic Failure System

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Abstract: *Brake failure in heavy commercial vehicles remains a major contributor to severe road accidents, financial loss, and fatalities worldwide. Conventional braking systems, primarily pneumatic or hydraulic, are prone to failure due to mechanical wear, fluid leakage, pressure loss, or system malfunction. To address this critical safety concern, this paper presents the design and analysis of an Alternative Braking System utilizing a Wheel Packing Mechanism as a mechanically independent fail-safe solution. The proposed system features a robust stopper mounted above the wheel, which, upon activation triggered either manually or automatically by brake system failure detection, engages the tire's outer surface to create direct frictional resistance, thereby decelerating the vehicle. Unlike conventional systems, this design eliminates dependency on electronic, pneumatic, or hydraulic subsystems, ensuring high reliability during emergencies. The system's components, including the fender support, friction pads, hydraulics, and stopping mechanism, are carefully designed for high strength, heat resistance, and durability. Structural and stress analysis using CAD and finite element analysis (FEA) tools validate the system's capability to withstand operational loads and stresses. While intended for emergency use to avoid collisions during total brake failure scenarios, this Wheel Packing Mechanism offers a practical, cost-effective, and retrofittable safety solution that enhances the overall braking safety of heavy-duty commercial vehicles.*

Keywords: Brake Failure, Alternative Braking System, Wheel Packing Mechanism, Heavy Commercial Vehicles, Emergency Brake Safety

I. INTRODUCTION

Braking systems are one of the most vital safety components in any automotive vehicle, particularly in heavy-duty commercial trucks that operate under extreme load conditions and travel long distances across varying terrains. These vehicles primarily depend on pneumatic and hydraulic braking systems that, while generally reliable, are still susceptible to various forms of failure such as air pressure loss, hydraulic fluid leakage, overheating, and component wear over time. The consequences of brake failure can be catastrophic, often leading to severe accidents, financial losses, property damage, and, in the worst cases, loss of life. This inherent risk highlights the urgent need for improved emergency braking solutions that can function independently of the primary braking system.

Although modern commercial vehicles incorporate advanced safety features like Anti-lock Braking Systems (ABS), Electronic Brake-force Distribution (EBD), and engine retarders, these systems fundamentally rely on the integrity of the primary braking circuit. Once a complete failure occurs in the main system, these advanced technologies become ineffective, leaving the vehicle without any viable means to slow down or stop. The situation becomes even more critical on highways, downhill gradients, and heavily trafficked routes where heavy trucks operate regularly. Current emergency measures such as runaway truck ramps are not universally available and depend heavily on the vehicle's proximity to these specially designed escape routes.

To address this critical safety gap, this study proposes the design and analysis of an **Alternative Braking System using a Wheel Packing Mechanism (WPM)**. Unlike traditional braking systems, the WPM operates entirely mechanically and is independent of pneumatic, hydraulic, or electronic controls. This feature ensures its reliability, particularly in

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situations where all other braking systems fail. The core principle involves deploying a high-friction mechanical stopper or block that directly engages the tire's outer tread surface, generating friction to slow down and eventually halt the vehicle. This simple yet effective solution provides a direct mechanical resistance against the wheel's rotation, making it highly dependable during emergencies.

The Wheel Packing Mechanism is designed to be activated either manually by the driver or automatically through sensors that monitor the status of the primary brake system. Upon detecting a failure, the system forces friction pads mounted within a robust stopper assembly to press against the tire surface. The generated friction converts the kinetic energy of the rotating wheels into heat, gradually reducing vehicle speed in a controlled manner. Though this process causes considerable tire wear and heat generation, it is specifically intended for emergency use and provides the driver with valuable time to regain control or bring the vehicle to a complete stop safely.

The design includes several key components: a fender supporter, fender, friction pads, hydraulic actuation mechanism, stopping mechanism, and the truck chassis interface. Each component is carefully designed and selected for optimal strength, durability, and heat resistance. For instance, materials like aluminum alloy and carbon steel are used for their excellent mechanical properties and resistance to operational stresses. Finite Element Analysis (FEA) simulations were carried out to validate the system's strength and effectiveness under various operational conditions. Stress, displacement, and force distribution analyses provide critical insights into the structural integrity and safety of the mechanism during emergency activation.

This paper elaborates on the complete design methodology, component selection, material analysis, and structural simulations involved in the development of the Wheel Packing Mechanism. The results demonstrate that the proposed system is capable of significantly enhancing vehicle safety by providing a fail-safe braking option that operates independently of conventional systems. Furthermore, the system's simple construction allows it to be retrofitted to existing heavy-duty vehicles, making it a cost-effective and practical solution for the transportation industry.

In conclusion, the Wheel Packing Mechanism represents a novel approach to enhancing the safety of heavy commercial vehicles by addressing one of their most dangerous failure scenarios—total brake failure. By introducing a mechanically independent braking alternative, this system contributes to reducing road accidents, saving lives, and protecting valuable cargo and infrastructure. The following sections of this paper present a comprehensive review of related works, detailed system design, material selection, simulation analysis, and potential implications for real-world application.

PROBLEM STATEMENT

Heavy commercial vehicles are highly vulnerable to catastrophic accidents in the event of total brake failure due to the limitations of conventional air or hydraulic braking systems. Existing safety features become ineffective once the primary brake system fails, leaving no reliable backup mechanism. There is a critical need for a mechanically independent emergency braking system that can safely halt the vehicle and prevent accidents.

II. LITERATURE SURVEY

The Importance and Role of Tyres on Road Vehicles: Their influence on Breaking Distance

It is considered that tyres play the primary role in terms of road safety on dry, wet, snowy or icy roads. This is due to their importance, as they are the element of support, of contact, of the car with the road (the track). This scientific paper presents concrete research carried out by the author with a view to implementing theoretical and practical concepts, in which the technical aspects of tyres fitted to road vehicles are presented. In this way, those interested can find out how tyres and wheel rims are labelled and marked; specific data are presented on summer and winter tyres; the phenomenon of of the aquaplaning of car wheels is defined, presented and explained; the forces and moments acting during braking are presented and defined; the braking distance (space) and the two second rule in road traffic are presented and explained.

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Stopping Sight Distance Parameters

A recent review of Stopping Sight Distance (SSD) parameters for the NCHRP has affirmed the adequacy of AASHTO's current 2.5-second driver perception-response time but recommended updates to braking distance assumptions. Existing AASHTO values, based on locked-wheel skidding on poor-condition wet pavement, were found to be insufficient at speeds above 30 mph, particularly for vehicles with minimum legal tire tread. The study concluded that braking distances should be increased—for example, to 360 feet at 40 mph and 1,630 feet at 80 mph— to ensure safe stopping within a lane under wet conditions. Despite these findings, it was recommended to retain the use of the same design speed for both wet and dry pavements, as drivers tend to maintain similar speeds regardless of surface condition. Additionally, a lower driver eye height of 40 inches (down from 42 inches) was proposed to better reflect the majority of modern vehicle-driver combinations. The study also showed that road segments with inadequate SSD experienced about 40% more crashes than nearby compliant locations, reinforcing the critical safety role of proper SSD design. Geometric design aids were developed to assist with SSD calculations on horizontal and vertical curves, including considerations for night visibility and object/eye position.

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Fabrication of Automatic Tire Inflating System

Driven by studies that show that a drop in tire pressure by just a few PSI can result in the reduction of gas mileage, tire life, safety, and vehicle performance, we have developed an automatic, self-inflating tire system that ensures that tires are properly inflated at all times. Our design proposes and successfully implements the use of a portable compressor that will supply air to all four tires via hoses and a rotary joint fixed between the wheel spindle and wheel hub at each wheel. The rotary joints effectively allow air to be channeled to the tires without the tangling of hoses. With the recent oil price hikes and growing concern of environmental issues, this system addresses a potential improvement in gas mileage; tire wear reduction; and an increase in handling and tire performance in diverse conditions

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Common faults and solutions of air brake system

Air brake system is a kind of brake system commonly used by large trucks, buses and other large vehicles. Air brake system structure is more precise, high frequency of use, so it is often prone to failure of a part. Once the air brake system fails, it is not only easy to affect the normal use of the vehicle, but also bring damage to the safety of the vehicle. Therefore, improving the reliability of the air brake system, reducing its failure rate and improving its troubleshooting level is an important principle to ensure its safe use. This paper mainly analysis and discusses the common faults and solutions of air brake system, and sums up some common points effectively. The failure of air brake system is one of the common faults of large vehicles. It will not only affect the normal use of the vehicle, but also bring damage to the safety of the vehicle

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III. METHODOLOGY

The methodology adopted for the development and analysis of the Alternative Braking System using the Wheel Packing Mechanism consists of multiple systematic stages as described below.

A. Problem Identification

The first step involved identifying the need for an emergency braking system that operates independently of conventional hydraulic, pneumatic, or electronic systems. Existing systems were analyzed for failure modes, and the critical safety gap during total brake failure was recognized.

B. Conceptual Design

Based on the problem analysis, a wheel packing mechanism was conceptualized. The design involves a mechanical stopper, positioned above the wheel, which is deployed directly onto the tire tread to create friction and bring the vehicle to a stop during emergencies.

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C. Design Modification

Several design iterations were carried out to optimize the size, shape, and positioning of the mechanical stopper and supporting components such as the fender, fender supporter, and hydraulic actuation unit. Considerations such as load distribution, mounting location, and ease of retrofit onto existing vehicles were factored into the design.

D. CAD Modeling

The finalized design was modeled using SOLIDWORKS CAD software. This 3D model allowed visualization of the complete assembly, identification of possible interferences, and served as the foundation for further analysis.

E. Finite Element Analysis (FEA)

Structural analysis was performed using Finite Element Analysis to simulate the mechanical behavior of the system under load. Material properties for aluminum alloy and carbon steel were assigned to different components. The simulation analyzed stress distribution, deformation, and safety factors under emergency braking conditions.

F. Force Application Simulation

The mechanical stopper's engagement force was simulated to evaluate its capacity to generate sufficient friction for deceleration while maintaining structural integrity under real-world conditions.

G. Validation and Optimization

The design was validated based on the simulation outcomes. Optimization was performed by adjusting component thicknesses, material choices, and hydraulic actuation parameters to achieve the best balance of strength, durability, and weight.

H. Safety and Failure Mode Consideration

Potential failure modes such as excessive tire wear, heat generation, and mechanical failure of the stopper were evaluated. The system is designed for one-time or limited-use emergency scenarios, minimizing continuous operational stresses.

This structured approach ensures that the Wheel Packing Mechanism is not only functionally effective but also safe, practical, and feasible for real-world applications in heavy-duty commercial vehicles.

IV. OVERVIEW OF WHEEL PACKING SYSTEM

The Wheel Packing System serves as a mechanically independent, emergency braking solution designed specifically for heavy commercial vehicles facing total brake failure. Unlike conventional braking mechanisms that rely on internal drum or disc systems, the Wheel Packing System operates externally by directly applying friction to the tire surface.

A. System Components

The complete assembly comprises several critical components, each designed for durability and functionality under emergency conditions:

Fender Supporter:

This structural element securely holds the fender and the stopper mechanism in place. It is fabricated from corrosion-resistant materials such as aluminum alloy or carbon steel, ensuring stability and alignment during high-stress scenarios.

Fender:

The fender serves both protective and functional roles by covering the tire and housing the wheel packing system. It prevents debris and road particles from interfering with the mechanism during its operation.

Friction Pads:

Friction pads are the core contact elements of the system. Constructed from high-friction rubber compounds reinforced with fibers, these pads provide the necessary resistance when pressed against the rotating tire. They are designed to withstand significant heat and wear during activation.

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Hydraulic Actuator:
The hydraulic system actuates the stopper, pressing the friction pads against the tire with controlled force. Pascal's Law allows a small input pressure to generate sufficient braking force for heavy vehicles, ensuring effective deceleration.

Stopping Mechanism:
The stopping mechanism includes both the hydraulic actuator and the mechanical linkage that guides the stopper into position. It ensures controlled engagement and uniform pressure distribution across the tire's surface.

Chassis Interface:
The system integrates with the vehicle's ladder-type chassis, which provides the necessary structural support for mounting and operation.

B. Working Principle
Upon detection of brake system failure—either manually by the driver or automatically through integrated sensors—the hydraulic actuator receives a signal to deploy the wheel packing mechanism. The friction pads are lowered onto the outer tread surface of the tire, creating immediate frictional resistance. As the pads press against the rotating wheel, kinetic energy is converted into heat, gradually slowing and eventually stopping the vehicle.

C. Safety and Operational Characteristics
Independent Operation:
The system functions independently of existing air or hydraulic brake circuits, offering a redundant layer of safety.

Fail-Safe Design:
Even in the absence of power or compressed air, the system can be manually activated to ensure vehicle stoppage.

Emergency Use:
Due to rapid tire wear and heat buildup, the mechanism is primarily intended for one-time or limited-use emergency scenarios.

Material Strength:
Aluminum alloys and carbon steel components ensure high structural integrity under extreme loads, while rubber friction pads provide high thermal and frictional performance.

By directly addressing brake failure risks with a simple, robust, and mechanically independent solution, the Wheel Packing System enhances safety for commercial vehicles operating under challenging conditions.

V. SELECTION OF MATERIAL AND ITS ANALYSIS
The selection of materials for the Wheel Packing System is critical to ensure its functionality, durability, and safety under emergency conditions. Each component is selected based on its mechanical properties, thermal resistance, weight, and cost-effectiveness. Additionally, finite element analysis (FEA) is conducted to validate the performance of selected materials under operational loads.

A. Material Selection
Aluminum Alloy:
Aluminum alloys are primarily used for structural components such as the fender supporter and frame assemblies. These alloys offer high strength-to-weight ratios, excellent corrosion resistance, and ease of manufacturing. Specifically, heat-treatable wrought aluminum alloys (e.g., 6xxx series) are selected for their superior mechanical properties, making them ideal for the support structure that bears the mechanical load during braking.

Carbon Steel:
Carbon steel is employed for highly stressed and load-bearing components such as the stopping mechanism arms and mounting brackets. Medium-carbon steel (0.3–0.6% carbon content) offers a balanced combination of strength, hardness, and ductility, while maintaining cost-effectiveness. The steel parts are further treated with anti-corrosion coatings to enhance their durability in harsh environments.

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Rubber-Based Friction Pads:
The friction interface utilizes high-friction rubber materials reinforced with fibers and filled with carbon black to improve wear resistance and thermal stability. Rubber's high coefficient of friction ensures maximum contact and energy dissipation during emergency braking, while its elastic properties allow it to conform to the tire surface, maximizing braking efficiency.

B. Finite Element Analysis (FEA)

Finite element analysis was performed to verify the mechanical performance of the selected materials under simulated emergency braking conditions. The analysis followed a three-stage process: preprocessing, processing, and post-processing.

Preprocessing:
The CAD model of the assembly was created using SOLIDWORKS.
Material properties such as Young's modulus, Poisson's ratio, and density were assigned to each component.
Appropriate boundary conditions, constraints, and loads simulating braking force were applied.
The model was meshed into finite elements to ensure accurate simulation.

Processing:
The simulation was executed to compute stress distribution, displacement, and reaction forces within the assembly.
Von Mises stress values were analyzed to determine regions of maximum stress and potential failure.

Post-processing:
The results indicated that both aluminum alloy and carbon steel components remained well within their yield limits under maximum braking load.
The maximum displacement observed was minimal, ensuring structural integrity and controlled braking behavior.

C. Simulation Results

Maximum Von Mises Stress: The highest stress concentration was observed at the contact points of the stopping mechanism but remained within allowable safety margins.

Maximum Displacement: The assembly exhibited minimal deformation under full load, confirming adequate stiffness and strength.

Thermal Considerations: The rubber friction pads showed acceptable thermal behavior for single-use emergency applications, although extended use may lead to overheating and material degradation.

D. Conclusion of Material Analysis

The combination of aluminum alloy, carbon steel, and rubber-based friction materials provides an optimal balance of strength, weight, and performance. The FEA results validate the design's ability to withstand the high forces encountered during emergency braking scenarios, ensuring safe and effective vehicle stoppage.

VI. RESULTS &OBSERVATIONS

The simulation results of the Wheel Packing System confirm that the design effectively withstands the high loads encountered during emergency braking. The maximum Von Mises stress remained within the material limits, ensuring structural safety. The maximum displacement observed was minimal, indicating sufficient rigidity and stability of the system. The friction pads successfully generated the required stopping force, validating the system's capability to bring the vehicle to a safe stop under brake failure conditions. Overall, the system demonstrated reliable performance, safety, and practical applicability for emergency use in heavy vehicles.

VII. CONCLUSION

The proposed Alternative Braking System utilizing a Wheel Packing Mechanism offers a reliable, mechanically independent solution for addressing total brake failure in heavy commercial vehicles. By employing a simple friction-based stopper that directly engages with the tire surface, the system ensures controlled deceleration even in the absence of conventional braking systems. The use of robust materials such as aluminum alloy, carbon steel, and high-friction rubber ensures durability, structural integrity, and effective energy dissipation during emergency scenarios. Finite element analysis has validated the system's capability to withstand operational loads, with minimal displacement and stresses within safe limits. This design not only enhances vehicle safety but also presents a cost-effective, easily retrofittable solution, contributing significantly to reducing accidents and improving road safety in the heavy transport sector.

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