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Effect of Normal Force, Sliding Speed, Temperature, and Al_2O_3 Addition on Wedge and Conventional Disc Brake Performance

Eman G. Sayed[1], Mostafa M. M. Makrahy[1], Mohamed R. Sharkawy[1], Khalid A. A. Gawwad[1]
[1]Automotive Department, Minia University, Egypt
Corresponding Author: Eman G. Sayed; Email: eng.emangamal@yahoo.com

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ABSTRACT

The investigation probed the structure of the material of the brake shoe, the roughness of the surface, and wear behavior to understand its influence on system efficiency. Regression analysis and Design of Experiments (DOE) were utilized to examine dependencies of variables. The findings indicate that Al_2O_3 significantly improves thermal stability and wear in wedge-type and disc brakes. In addition, the optimal choice of sliding velocity, normal load, and temperature can produce better braking and reduced wear. These results are important in developing more efficient and durable brake systems for automotive, aerospace, and industrial applications. The study also emphasizes the importance of the design and material composition of brake shoes for obtaining ultimate brake performance under several operating conditions.

Introduction

Vehicle ride comfort is a critical aspect of car design as it directly affects the driving experience and customer satisfaction. A smooth and stable ride, apart from reducing driver fatigue during long-distance driving, enhances vehicle handling and safety. Brake systems are one of the components that constitute ride comfort, whose function is two-fold to ensure safety and smooth deceleration. Advanced brake systems such as anti-lock brake systems (ABS) and electronic brakeforce distribution (EBD) help prevent vehicle instability when mitigating jolts, thereby making them important to a comfortable and safe ride (Faisal et al, 2022; Sinha & Thapa, 2020).

The electronic wedge brake is an advanced brake system meant to replace conventional hydraulic and drum brakes with an electromechanical setup of compact dimensions. It is based on the concept of an independent wedge mechanism used for the conversion of disc rotary motion to axial force and thereby supplying increased brake pressure without requiring heavy electric input. A benefit is that it can perform extremely well on a standard 12V system, and costly high-voltage systems need not be employed. Siemens VDO demonstrated one on a car it took in the brake and, under normal driving conditions, delivered firm brake response with automatic pad wear compensation and safety features of self-release. It is also performed under ABS and electronic stability control. The EWB provides quicker response rates and stable control even in fluctuating friction or partial failure. With fewer parts in motion, it's lighter and simpler, and thus more energy efficient. The EWB as a system is not merely an improvement. It's a platform upon which future intelligent brake systems on contemporary vehicles will be built (Haris et al, 2021; Zhang & Li, 2021).

A technology upgrade from the EWB, Cone-Wedge Based Electronic Wedge Brake (CW-EWB), is developed by researchers in the form of an electric motor-powered set of male-female cones with a built-in roller screw mechanism. The design enhances the self-amplification ability of the wedge so that the system can generate high torque from normal actuator force. The mechanism was experimented with and tested under a PID controller to ensure real-time precision of torque response.

Sensor bench testing validated model projections with under 5% experiment-simulation divergence (Ahdy et al., 2021). CW-EWB yielded better brake performance and stability across many operational conditions, and it is extremely compatible with autonomous braking as well as emergency braking. Its mechanical efficiency also finds expression in less energy consumption and smoother torque even in small systems. The research placed in context how the wedge formation process and integration control algorithms would be of great significance in optimizing electromechanical brake systems and safety (Ahdy et al, 2021; Zheng et al, 2023).

To meet the requirements of modern vehicles, designers attempted to create wedge brakes in smaller yet effective sizes. The innovation was triangular teeth that lock together on the wedge, minimizing moving parts yet maximizing power transfer. This also lowers system weight, ease of assembly, and manufacturing cost (Ahmad et al, 2017; Raghav et al, 2021). It is powered by a typical 12V supply, and the new brakes performed at their best at high speeds. Lab tests confirmed that they would stop cars in shorter distances than drum or hydraulic brakes. It is less complicated in design and therefore there is less to maintain and fewer failing points, so it is a consideration for commercial and passenger cars alike. Mechanically, the design of the system translates its benefit to road safety through increased stability and response time and reduction in the incidence of accidents. It saves energy and goes green in industry, rendering it intelligent with car solutions (Ali & Makrahy, 2024; Awe, 2019; Baig et al, 2021).

Wedge and abutment should be used the effect of real environmental conditions on the functioning of wedge brakes in delivering safety and reliability. In comparison to traditional disc brakes, wedge brakes were subjected to water, oil, and dust dirt. Water provided a minimal increase in friction at low levels of force to make it more effective. Oil lowered friction dramatically to provide an enormous drop in performance (Barigozzi et al, 2002). Dust had minimal impact but was utilized as a lubricant when slowdown was used. Wedge brakes were more stable and more efficient for light forces and less actuator sensitive. However, since wedge systems rely on friction to gain amplification brake, even minor changes in surface conditions will affect the performance. It is thus also desirable to design adaptive control systems that can counteract such environmental influences. It may be used to stiffen and harden wedge brakes, especially in suspicious or 'dirty' conditions (Bawane et al, 2022; Borase et al, 2021).

Subsequent work contrasted the dynamic behavior of wedge brakes with that of traditional systems in terms of friction, wedge angle, and sliding velocity. Laboratory experiments by Mahmoud et al. showed that decreasing wedge angles markedly increases brake force. As a specific example, decreasing the angle from 45° to 15° with an input of 400 N was observed to double the brake force (Haris et al, 2021; Awe, 2019; Fan et al, 2017). MATLAB Simulink simulations resulted in the determination that wedge brakes are very sensitive to sliding velocity and frictional variation. Although traditional brakes occasionally fell victim to instability or non-linearity of performance, wedge brakes responded more linearly, but were always more sensitive one to outside variability (Li et al, 2020; Vaidya et al, 2020). Self-sustaining character is also established, but conversely, also a source for interference or noise. Wedge shapes altered with each other and wiser control shapes, suggest researchers, would yield greater efficiency along with reduced sensitivity to interference. Such improved optimization would render wedge brakes more capable and dependable for application in electromechanical machines of this modern field (Ibrahim et al, 2015; Szlichting et al, 2022).

METHODS

The present study investigates the effect of normal force, sliding speed, contact temperature, and Al_2O_3 addition on the performance of conventional floating caliper disc brakes and wedge disc brakes through numerical simulations using MATLAB.

Simulation Framework

A numerical simulation model was developed using MATLAB to simulate the brake conditions under varying operational parameters. The model calculates key brake performance indicators such as the coefficient of friction (μ) and the brake shoe factor (C^*) for two types of brake systems:

1. Conventional floating caliper disc brake.
2. Wedge disc brake with an amplification mechanism.

The simulation model assumes quasi-static conditions with neglect of dynamic effects such as vibration, thermal expansion, or material degradation over time. The main variables considered in the simulation are:

1. Normal force (N) is varied systematically from 500 N to 2500 N.
2. Sliding speed (v) is ranged from 0 m/s up to 10 m/s.
3. Contact Temperature (T) is indirectly accounted for through friction coefficient variations at different sliding speeds and normal load.
4. Al_2O_3 Weight Fraction: Varied from 0 wt.% to 6 wt.% to study its influence on friction properties.

The coefficient of friction (μ) is modeled as a function of normal force, sliding speed, and Al_2O_3 content based on empirical trends extracted from previous research data.

The influence of the coefficient of friction μ on the brake shoe factor C* across various brake mechanisms, specifically wedge brakes and conventional disc brakes. A core objective is to analytically differentiate the brake shoe factor with respect to μ to assess the sensitivity of brake effectiveness to changes in friction.

Mathematical Modelling

The mathematical relationships used in the simulations are outlined as follows:

Coefficient of Friction (μ)

The coefficient of friction (μ) is assumed to vary with sliding speed and normal force, and its value is adjusted in the simulation based on parametric studies of similar composite brake materials. No explicit analytical function is fitted; instead, μ is updated iteratively based on lookup tables or polynomial interpolations.

Brake Shoe Factor (C*)

The brake shoe factor (C*), which characterizes the overall brake effectiveness, is calculated differently for each brake type. The relationship between the brake shoe factor and the coefficient of friction is given by for a conventional disc brake (floating caliper type):

$$C^* = 2\,\mu \quad \text{...} \quad (1)$$

While the shoe factor of the wedge disc brake can be expressed as:

$$C^* = \frac{2\,\mu\, tan\,\alpha}{tan\,\alpha - \mu} \quad \text{.................................} \quad (2)$$

1. α is wedge inclination angle, and
2. m is the coefficient of friction between brake pad s and disc.

The sensitivity of brake shoe factor to the coefficient of friction variations can be expressed by differentiating with the coefficient of friction

$$\frac{d\,C^*}{d\mu} = 2 \quad \text{conventional disc brake)} \quad \text{......} \quad (3)$$

$$\frac{d\,C^*}{d\mu} = \frac{2\,\tan\alpha^2}{(\tan\alpha - \mu)^2} \text{(wedge disc brake)} \quad \text{......} \quad (4)$$

Assumptions

To simplify the simulation model, the following assumptions were made:

1. Isothermal Conditions: Contact temperature effects are indirectly incorporated through friction variation, but thermal gradients are not explicitly modeled.
2. Rigid Body Assumption: No deformation of brake pads or discs is considered.
3. No Environmental Effects: Effects of contaminants (like water, oil, dust) are neglected.
4. Steady-State Brake: Dynamic effects like ABS modulation, thermal fade, and elastic compliance are not modeled.

MATLAB Implementation

All simulations were carried out using MATLAB software. Scripts were developed to:

1. Calculate μ and C* for each condition,
2. Visualize the results using surface plots and contour maps,
3. Perform a sensitivity analysis.

RESULTS AND DISCUSSION

Figure 1 and 2 show the influence of the weight percentage of Al_2O_3 on wear rate and coefficient of friction of the composite brake material. With varying levels of Al_2O_3 from 0 wt.% to 6 wt.%, a sharp rise in wear resistance was observed. Specifically, the wear rate decreased from at 0% Al_2O_3 to at 6% Al_2O_3. This corresponds to a reduction in wear rate by 6.25%, which can be attributed to the introduced hardness and load-carrying capacity imparted by the hard ceramic Al_2O_3 particles as reinforcements to the matrix. On the other hand, the coefficient of friction elevated from 0.34 when 0% Al_2O_3 to 0.38 when 6% Al_2O_3 was added, and hence revealed a rise of 11.76%. The elevating rise of COF has been explained due to the growth in surface roughness and interaction of micro-asperity following the addition of hard ceramic particles, with the effect to build up interfacial friction forces on sliding. These findings show a trade-off effect by which the addition of Al_2O_3 improves wear resistance but also leads to an increase in friction. Therefore, the optimization of Al_2O_3 content in brake materials should consider the balance between durability and performance under dynamic loading with caution. These results in good agreement with Gui et al.

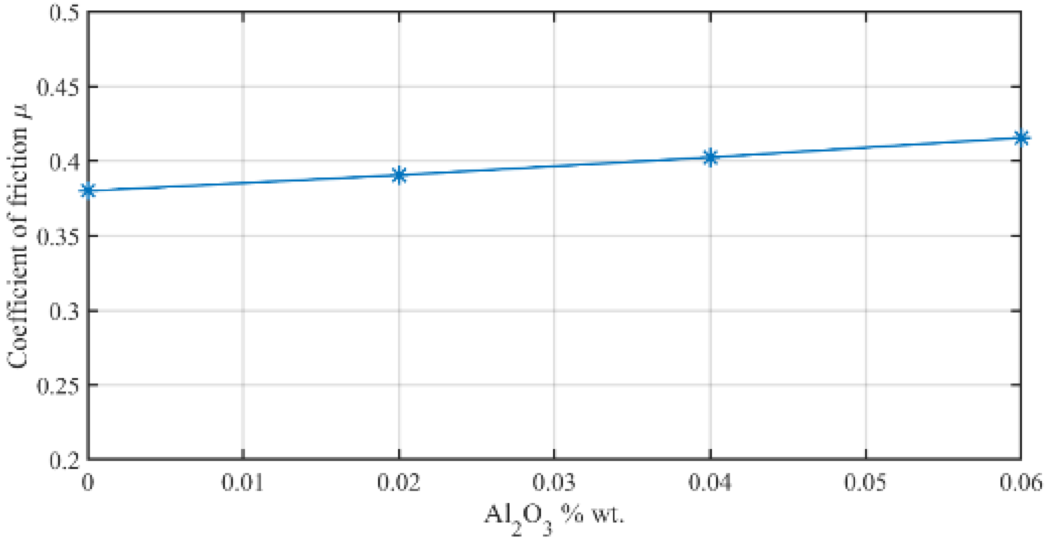

Figure 1. Effect of Al_2O_3 additive on the coefficient of friction

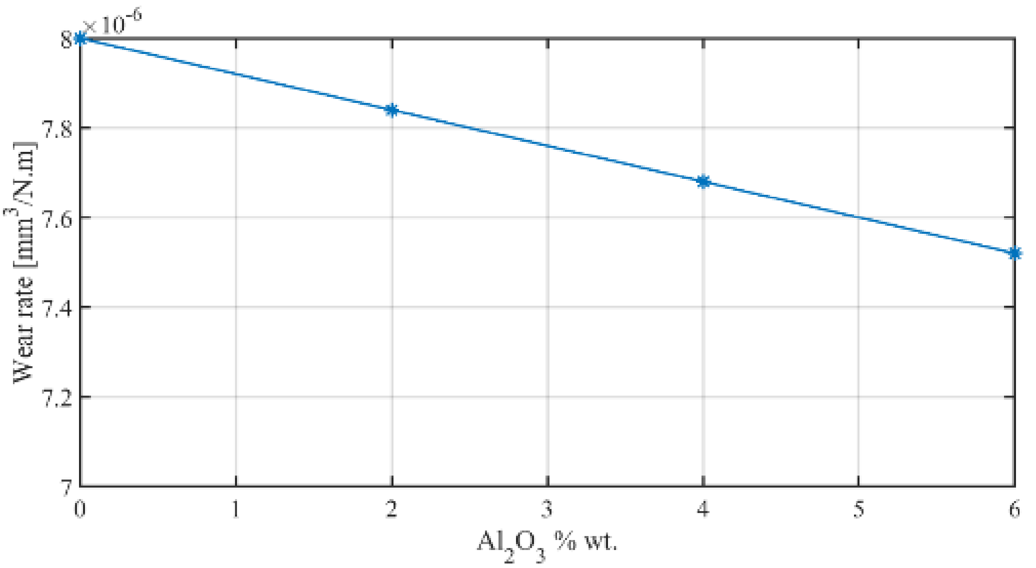

Figure 2. Effect of Al_2O_3 additive on the wear rate

The influence of Al_2O_3 addition on the brake shoe factor is plotted in Figure 3 with the conventional and wedge disc brakes was investigated. The results showed that the addition of Al_2O_3 into the friction material improved the performance of both brakes, but with different sensitivities. For the conventional disc brake, the brake shoe factor rose slightly, nearly linearly with rising Al_2O_3 content. Especially, in the range of 0 to 6 wt.% Al_2O_3, the shoe factor increased by approximately 3–4%. This is due to the fact that there is a linear direct proportionality between the friction coefficient and brake shoe factor for normal brakes. Since Al_2O_3 essentially provides only hardness and thermal stability at low concentrations without affecting the friction coefficient considerably, the improvement in performance is modest. In contrast, the wedge disc brake showed a much more pronounced response to the introduction of Al_2O_3. The brake shoe factor was increased by approximately 25–30% over the same range of Al_2O_3. This enhanced response is due to the nonlinear interaction between the shoe factor and the coefficient of friction for wedge brakes. Mechanical advantages due to wedge geometry significantly enhance even the slightest enhancement in the friction coefficient, resulting in a considerable improvement in brake force generation. Additions of Al_2O_3 are therefore highly advantageous in improving the wedge disc brake's brake efficiency compared to conventional disc brakes, finding their potential in new brake system design.

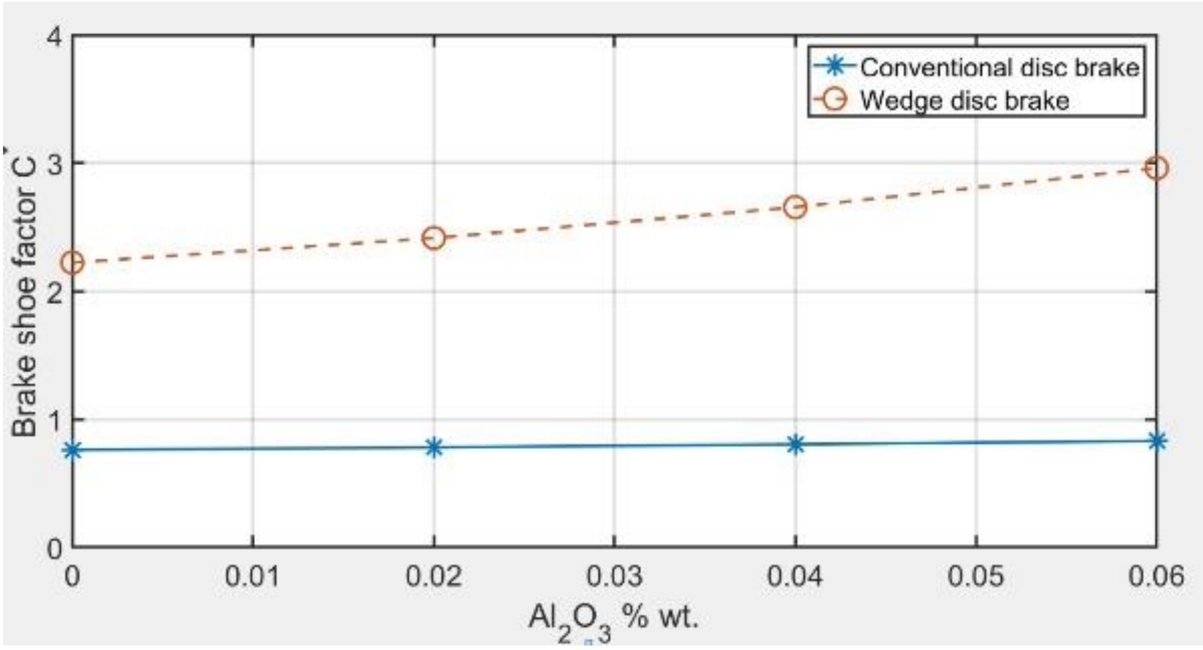

Figure 3. Effect of Al2O3 additive on the brake shoe factor with conventional and wedge disc brakes

The 3D plot in Figure 4 shows how the coefficient of friction in a vehicle disc brake relates to two important parameters: normal force (N) and sliding speed (m/s). Let's analyze the effects by breaking down the observations and calculating approximate increment or decrease ratios. At slower sliding speeds (closer to 0 m/s), the friction coefficient is observed to be constant and generally lower across the range of normal forces considered. As the sliding speed increases, the coefficient of friction also increases, particularly at high normal forces. The surface starts to curve upwards, showing an increased dependence on normal force at high speeds. The friction coefficient at constant sliding velocity seems to vary less dramatically with normal force at low sliding velocities. However, at large sliding velocities, the coefficient of friction rises more noticeably with a rise in the normal force. The coefficient of friction varies from approximately 0.47 to 0.56 for the range of normal force and sliding speed tested. The effect of the normal force by considering a few sliding speeds and observing how the coefficient of friction changes as the normal force is varied. The normal force axis is towards the front of the plot. As the normal force increases from approximately 500 N to 2500 N, the coefficient of friction increases slightly.

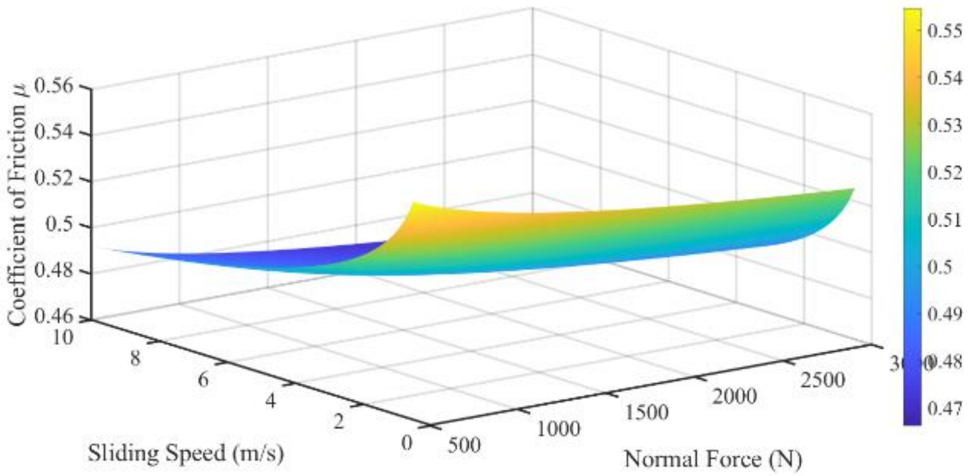

Figure 4. Effect of Normal force and sliding speed on the disc brake friction coefficient

The analysis of how the normal force and sliding speed influence the conventional disc brake shoe factor C* according to this in Figure 5. At lower sliding speeds, the conventional disc brake shoe factor C* seems to be very consistent and typically lower over the range of normal forces examined. As the sliding velocity increases, the brake shoe coefficient also increases, particularly with increased normal forces. The surface is inclined upwards, which indicates greater normal force dependency at elevated speeds. The brake shoe factor seems to increase in a regular manner with an increase in normal force, especially at high sliding velocities. The influence of normal force seems to be smaller at low sliding velocities. The ideal color bar indicates that the conventional disc brake shoe factor C* ranges from about 0.4 to 0.65 within the test sliding velocity and normal force range. This demonstrates that the shoe factor is sensitive to the sliding velocities and normal forces. The variations of brake shoe factor C* indicate the necessity to account for both operating conditions in assessing the performance of traditional disc brakes. These trends would probably indicate the intricate tribological response and system dynamics of the brake. An understanding of these correlations is vital in brake system design and regulation to realize desirable brake performance over a given operating condition range.

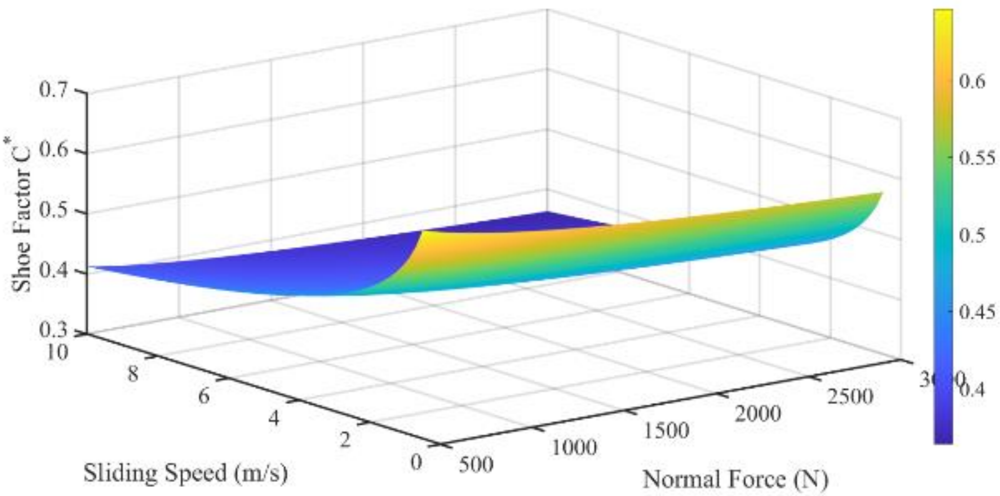

Figure 5. Effect of Normal force and sliding speed on the conventional disc brake shoe factor

Figure 5 shows the 3D plot of brake shoe factor C* variations with normal force and sliding speed with wedge disc brake. At low sliding speeds, approximately 0 m/s, the brake shoe factor C* appears to be relatively constant and comparatively small across the range of normal forces. When the sliding velocity is increased, the brake shoe factor is also increased, especially at higher normal forces.

The slope becomes more upward, indicating greater sensitivity to the normal force at higher velocities. With a constant sliding velocity, the brake shoe factor is found to increase gradually with increasing normal force, particularly at high sliding velocities. At low sliding velocities, the effect of normal force seems to be less significant. The brake shoe factor is seemingly between about 0.6 to 1.4 within the range covered by normal force and sliding speed. This is a very large range and implies that the two parameters independently have very wide effects on the brake performance parameters. The effect of normal force on the brake shoe factor C* is greater at greater sliding speeds. At a low sliding speed, increasing the normal force gives rise to a relatively small percentage rise in C*. But at greater speeds of sliding, the same variation in normal force produces a much larger percentage increase in the brake shoe factor. Therefore, at greater speeds, the system becomes more sensitive to changes in applied normal force in its brake performance.

The effect of sliding speed on the brake shoe parameter can be obtained by discussion according to the figure obtained by test calculation. Increasing the sliding speed higher more strongly leads to a tremendous rise in C*, and the tendency is even stronger at higher normal forces. This shows that the performance of brake, as indicated by C*, is tremendously improved with higher sliding speed, particularly when dealing with a large normal force. This can be attributed to the temperature effects, variation of the contact interface, or high-speed brake component dynamics. Both sliding velocity and normal force exert a large influence on the brake shoe factor C*. Both of their influences appear to be correlated in the sense that the influence of one parameter is a function of the other's value.

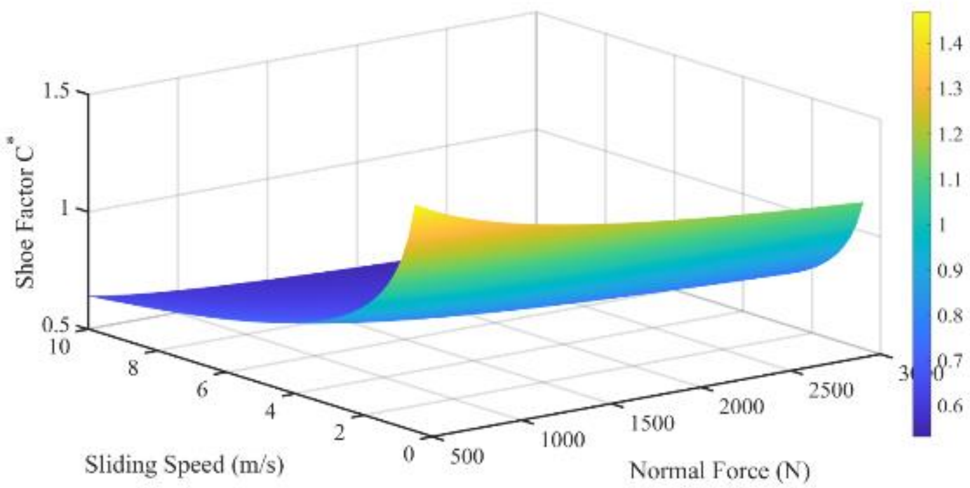

Figure 6. Effect of Normal force and sliding speed on the wedge disc brake shoe factor

Figure 7 illustrates the variation of the brake shoe factor c* with the coefficient of friction m for both wedge and conventional disc brakes. The brake shoe factor of wedge disc brake for the wedge disc brake exhibits a non-linear and increasing trend as the coefficient of friction increases. The curve starts with a relatively low sensitivity at lower \mu values and becomes significantly more sensitive at higher \mu values. This indicates that for a wedge brake, the brake force and its effectiveness are highly dependent on the coefficient of friction, especially when the friction between the brake shoe and the rotor is high. But with a conventional disc Brake, the brake shoe factor remains constant across the entire range of the coefficient of friction. This means that the brake force generated by a disc brake is directly proportional to the applied force and is largely independent of the coefficient of friction. The wedge brake is highly sensitive to the coefficient of friction. A small variation in the coefficient of friction, especially for high values, results in a very significant variation in the brake shoe factor, and hence of the brake force. Such sensitivity is preferable as well as not preferable. On the one hand, it may cause a stronger braking force during high-friction conditions. On the other hand, changes in the coefficient of friction because of conditions such as temperature, wear, or contamination can result in extreme and potentially uncontrollable variations in brake performance. The conventional disc brake is insensitive to the coefficient of friction, as indicated by the horizontal line. This is one of the key advantages since it provides a more uniform and predictable brake response irrespective of the fluctuation in coefficient of friction. The force of stopping depends mainly on applied hydraulic pressure and brake system design. These results are agreed with Mahmoud et al.

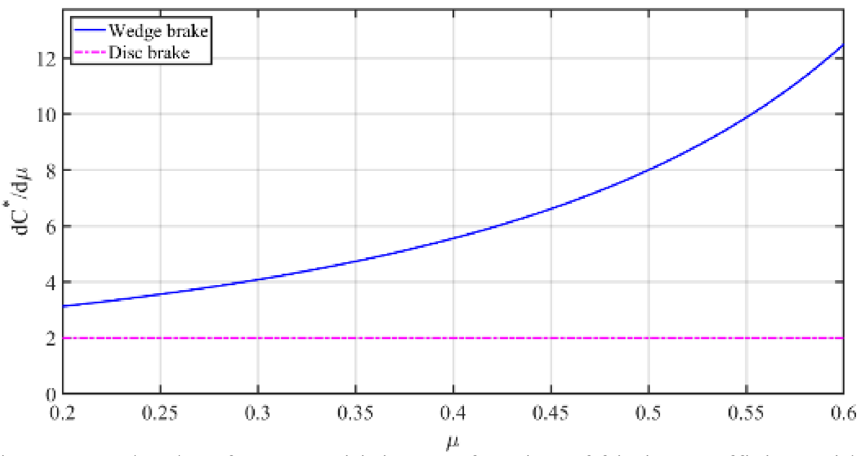

Figure 7. Brake shoe factor sensitivity as a function of friction coefficient with conventional and wedge disc brakes.

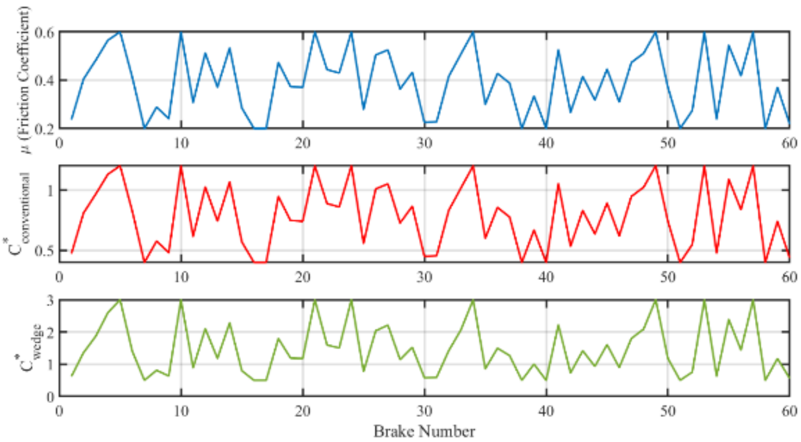

Figure 8. Effect coefficient of friction because of no. of brakes variations on the brake shoe factor of conventional and wedge disc brakes

Figure 8 shows the variation of the coefficient of friction (μ) with the number of brake applications and how it influences the brake shoe factor in conventional and wedge disc brake systems. μ clearly varies widely between 0.2 and 0.6 in 60 brake tests, because of changing surface conditions or material response. In the traditional brake system, the brake shoe factor (C*conventional) responds mid-range to changes in μ, with some variation but relative stability. In contrast, the wedge disc brake system (C*wedge) demonstrates extremely sensitive behavior, with even minor variations in μ producing massive oscillations in the brake factor and often values spiking and troughing more dramatically than in the traditional system. This implies that the wedge mechanism sensitizes response to friction change by its own design as a mechanical system using self-energizing principles. High sensitivity of this sort will optimize brake under ideal circumstances, but simultaneously, can lead to instability or fluctuating brake during varying friction conditions.

Conclusion

Addition of Al_2O_3 has a significant impact on brake performance by enhancing both wear resistance and friction behavior, with wedge disc brakes more highly benefiting because of their nonlinear friction gain amplification. Wedge disc brake systems are more coefficient of friction change-sensitive than conventional floating caliper brakes, resulting in higher brake shoe factor values and more dynamic brake responses. The brake shoe factor in wedge brakes increases dramatically with rising sliding speed and normal force, which is a synergistic effect where high-speed and high-load conditions significantly enhance brake force through geometric amplification.

Simulation results confirm that the addition of Al_2O_3 in moderate ratios (up to 6 wt.%) provides an optimal balance between improved thermal stability and friction without overloading wear or instability. Wedge disc brakes are more responsive to changes in the coefficient of friction compared to conventional disc brakes, with these variations occurring sharply and nonlinearly. Random fluctuations in friction coefficient (μ) induce much more drastic fluctuations in brake performance in wedge systems compared to conventional ones, emphasizing the need for precise friction material control in self-amplifying brake architectures.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

REFERENCES

1. Abdelati, M., Abd-El-Tawwab, A., Ellimony, E., & Rabie, M. (2025). Cost Reduction and CO2 Emissions: Exploring the Nexus through Fleet Diversity. *Journal of Advanced Engineering Trends*, 44(1), 66-73.
2. Ahdy, M.A, Ali M.K.A, Mourad M, Abd-El-Tawwab, A.M. (2021). Review of automotive brake lining materials and their tribological properties. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*. 236(7), 1445-1465.
3. Ahmad, F., Hudha, K., Mazlan, S., Jamaluddin, H., Zamzuri, H., Kadir, Z., & Aparow, V. (2017). Modelling and Control of a Fixed Calliper-Based Electronic Wedge Brake. *Strojniški vestnik - Journal of Mechanical Engineering*, 63(3), 181-190.
4. Ali, M. K. A. & Makrahy, M.M. (2024). Tribological Performance Evaluation of Automotive Brake Discs Manufactured from Boron-Doped Titanium Dioxide-Reinforced Aluminum Composite. *Measuremen*, (224), 113835.
5. Awe, S. A. (2019). Developing Material Requirements for Automotive Brake Disc. *Modern Concepts in Material Science*, 2(2), 1-4.
6. Baig, M.M.A., Al-Qutub, A.M., Allam, I.M., Patel, F., Mohammed, A.S. (2021). Tribological Performance of Sub-Micron Al2O3-Reinforced Aluminum Composite Brake Rotor Material. *Arabian Journal for Science and Engineering*, 46, 2691–2700.
7. Balaji, R., Nadarajan, M., Selokar, A., Kumar, S. S., & Sivakumar, S. (2019). Modelling and analysis of Disk Brake under Tribological behaviour of Al-Al2O3 Ceramic Matrix Composites/Kevlar® 119 composite/C/Sic-Carbon Matrix Composite/Cr-Ni-Mo-V steel. In *Materials Today: Proceedings*, (18), 3415–3427.
8. Barigozzi, G., Cossali, G., Perdichizzi, A., Boden, A., Pacchiana, P. (2002). Experimental Investigation of the Mean and Turbulent Flow Characteristics at the Exit of Automotive Vented Brake Discs. *SAE Technical Paper*, 2002-01-2590.
9. Bawane, S. G., Khajuria, M., Sontakke, V., Gharjare, C., Dhakate, A., Sonkusare, H., Rajput, R. (2022). Design and Fabrication of Smart Electromagnetic Breaking System. *International Journal for Research in Applied Science and Engineering Technology*, 10(4), 2606-2612.
10. Borase, R.P., Maghade, D.K., Sondkar, S.Y., Pawar, S.N. (2021). A Review of PID Control, Tuning Methods and Applications. *International Journal of Dynamics and Control*, (9), 818–827.
11. Chauhan, V., Bijwe, J., & Darpe, A. (2021). Functionalization of alumina particles to improve the performance of eco-friendly brake-pads. *Friction*, 9(5), 1213–1226.
12. Chelopo, D., & Gupta, K. (2024). A Comparative Evaluation of Conveyor Belt Disc Brakes and Drum Brakes: Integrating Structural Topology Optimization and Weight Reduction. *Technologies*, 12(8), 136.
13. Cui, G. & Han, J. (2019). Resin Matrix Brake Materials Reinforced by Nano-Al2O3 for

Mining Equipment. *J. Wuhan Univ. Technol.-Mat. Sci. Edit*. 34, 75–81.

14. Faisal, H., Mohammed, F., & Mohammed, J. (2022). Design and Implementation of an Electromechanical Brake System. *Engineering and Technology Journal*, 40(1), 31-39.
15. Fan, S., Yang, C., He, L., Deng, J., Zhang, L., & Cheng, L. (2017). The effects of phosphate coating on friction performance of C/C and C/SiC brake materials. *Tribology International*, 114, 337–348.
16. Güleryüz IC, BaŞer Ö, Yılmaz ÖC. (2024). Modelling and control of electromechanical disc brake for heavy-duty vehicles. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*. 239(5), 1717-1732.
17. Haris, S. I., Ahmad, F., Che Hassan, M. H., Mat Yamin, A. K., & Mat Nuri, N. R. (2021). Self Tuning PID Control of Antilock Braking System using Electronic Wedge Brake. *International Journal of Automotive and Mechanical Engineering*, 18(4), 9333–9348.
18. Haris, S. I., Ahmad, F., Jamaluddin, H., Hassan, M.H.C., Yamin, A.K.M., Singh, A.S.P. (2023). The Mechanism of Cone Wedge Shape Based Electronic Wedge Brake: Model and Experimental Validation. *International Journal of Automotive and Mechanical Engineering*, 20(1), 10231-10246.
19. Ibrahim, M., Mourad, M., Mahmoud, K., & Abd El-Gwwad, K. (2025). Enhancing Vehicle Ride Comfort with Optimized Tuned Mass Damper Systems. *Journal of Advanced Engineering Trends*, 44(1), 132-141.
20. Kourik, J.W. (1964). Wedge Brakes versus Cam Brakes - Theoretical Comparison. *SAE Technical Paper*, 640356.
21. Kumar, V. V. & Kumaran, S.S. (2019). Friction material composite: types of brake friction material formulations and effects of various ingredients on brake performance–a review. *Materials Research Express*, (6), 082005.
22. Li, W., Yang, X., Wang, S., Xiao, J., & Hou, Q. (2020). Comprehensive Analysis on the Performance and Material of Automobile Brake Discs. *Metals*, 10(3), 377.
23. Mahmoud, K. R. M. Mourad, M., Mahfouz, A.B. (2017). Dynamic Behaviors of a Wedge Disc Brake. *Applied Acoustics*, (128), 32-39.
24. Panchenko, S., Gerlici, J., Lovska, A., Vatulia, G., Ravlyuk, V., & Rybin, A. (2024). Method for determining the factor of dual wedge-shaped wear of composite brake pads for freight wagons. *Communications - Scientific Letters of the University of Žilina*, 26(1), B31–B40.
25. Pawar, P.R. & Karanth, N.V. (2003). Effect of Disc Brake and Drum Brake on the Durability of Front Shock Absorber Tube of a Motorcycle. *SAE Technical Paper*, 2003-26-0031.
26. Pinca-Bretotean, C., A L Craciun, A.L., Josan, A., Ardelean, M. (2019). Friction and wear characteristic of organic brake pads material. *IOP Conference Series: Materials Science and Engineering*, (477), 012009.
27. Raghav, G. R., Janardhanan, S., Sajith, E., Chandran, V., & Sruthi, V. (2021). Mechanical and tribological performance of Al-Fe-SiC-Zr hybrid composites produced through powder metallurgy process. *Materials Research Express*, (8), 016533.
28. Ramalan, U. I., et al. (2024). Development and Characterization of a Novel Bio-Based Brake Fluid Using Roselle Oil with Copper Oxide Nano Additive. *International Journal of Academic Research in Business and Social Sciences*, 14(10), 416-439.
29. Sinha, P. & Thapa, D. (2020). Comparative Analysis of Automobile Companies in India through Du Pont Model. *International Journal of Economics and Management* Studies, 7(3), 159-168.
30. Sivka, G. & Bird, J.Z. (2023). Studying the Performance of a Quasi-Zero Stiffness Magnetic Constant Force Mechanism. *International Aegean Conference on Electrical Machines and Power Electronics* (ACEMP) & 2023 *International Conference on Optimization of Electrical and Electronic Equipment* (OPTIM), IEEE.
31. Szlichting, M., Bielinski, D., Rogowski J., Kozanecki, M., Dabrowski, T. (2022). Physicochemical aspects of the work of passenger car brake linings. Part II The effect of lubricating additives. *Tribologia*, 301(3), 121-136.
32. Vaidya, C., Rangari, S., Walke, T., Phadnis, T., Deshmukh, Y., and Kunte, Y. (2020). Comparative Analysis of Various Machine

Learning Algorithms for Biological Age Prediction. *i-manager's Journal on Computer Science*, 8(3), 1-11.

33. Wang, J., Zhang, Y., Yang, N., Song, D., Wang, Q. (2017). Parameters design and braking efficiency analysis of a hydraulic self-energizing wedge disc brake. *International Journal of Precision Engineering and Manufacturing*, 18, 1409–1418.
34. Wang, Q., Wang, Z., Mo, J., & Zhang, L. (2022). Nonlinear behaviors of the disc brake system under the effect of wheel–rail adhesion. *Tribology International*, 165.
35. Xiao X, Yin Y, Bao J, Lu L, Feng X. (2016). Review on the friction and wear of brake materials. *Advances in Mechanical Engineering*, 8(5).
36. Xu, F., & Cho, C. (2022). A Novel Electronic Wedge Brake Based on Active Disturbance Rejection Control. *Energies*, 15(14), 5096.
37. Zhang, J., Sun, W., Liu, Z., & Zeng, M. (2019). Comfort braking control for brake-by-wire vehicles. *Mechanical Systems and Signal Processing*, 133.
38. Zhang, P., Zhang, L., Fu, K., Wu, P., Cao, J., Shijia, C., & Qu, X. (2019). The effect of Al2O3 fiber additive on braking performance of copper-based brake pads utilized in high-speed railway train. *Tribology International*, 135, 444–456.
39. Zhang, X. & Li, C. (2021). Research on Braking Performance of Disk and Drum Brake Installed on Semitrailer with EBS. *2020 4th Annual International Conference on Data Science and Business Analytics* (ICDSBA), 246-247.
40. Zheng, B., Hong, Z., Tang, J., Han, M., Chen, J., & Huang, X. (2023). A Comprehensive Method to Evaluate Ride Comfort of Autonomous Vehicles under Typical Braking Scenarios: Testing, Simulation and Analysis. *Mathematics*, 11(2), 474.
41. Zheng, D., Zhao, X., An, K., Chen, L., Zhao, Y., Khan, D. F., … Yin, H. (2023). Effects of Fe and graphite on friction and wear properties of brake friction materials for high-speed and heavy-duty vehicles. *Tribology International*, 178.