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# Review on Study and Analysis of Disc Brake to Reduce Disc Brake Squeal

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**Abstract**
Brake squeal noise has been under investigation by automotive manufactures for many years due to consistent customer complaints and high warranty costs. Disc brake squeal remains a complex problem in the automotive industry, since the early 20th century, many researchers have examined the problem with experimental, analytical and computational techniques. Although brake squeal do not affect braking performance, still it is not acceptable. So brake noise issues have led vehicle manufacturers, brake and friction material suppliers to investigate various ways of improving their processes in order to reduce vehicle noise and increasing passenger comfort.
In this paper various parameters influencing disc brake squeal are studied from literatures. Various parameters are braking pressure, rotational velocity, coefficient of friction, damping, modifications in disc and pad. During braking operation braking pressure, rotational velocity are not in control. Decrease in coefficient of friction reduces the brake squeal, but it is not applicable because it lowers the braking performance. Damping shims to reduce squeal increases the cost of damping material. So best way to reduce disc brake squeal is structural modification in disc brake assembly.
***Keywords***: *Disc **brake, Squeal, FEA, EMA***

## 1. Introduction

Brake squeal is one of the most frequent field claims in automotive industry. Experts and scientists have been conducted researches over the decades in academics and industry. Friction induced vibrations are very common problems in engineering. Squealing of vehicle brakes is complex phenomenon and thus much effort is spent to overcome this problem. So its investigation requires expertise from different disciplines (e.g. vibrations, tribology, acoustics, etc.) as evidenced by the number of approaches to the problem and the variety of explanations on how brake squeal originates that have been proposed so far. However, there is no complete understanding of the problem and not a generalized theory of squeal mechanism. The high complexity of a brake system is the main difficulty encountered in studying brake squeal. Commonly, investigations are done by combining theory and experiments by most of research groups working on this subject. Many such studies started by performing experiments on simplified test rigs, trying to correlate the experimental results with theoretical models. The aim of studies is to get clear understanding of the squeal mechanisms and then to extend such knowledge to build complex models and, finally, to control the squeal occurrence in commercial brakes. Brake squeal is a high-pitched noise in the frequency range between 1 kHz and 16 kHz originating from self-excited vibrations which are caused by the frictional contact between brake pads and brake disc.

### 1.1 Components of Disc Brake

There are several major components of a disc brake: the rotor, caliper, brake pad assemblies and a hydraulic actuation system. The rotor (or disc) is rigidly mounted on the axle hub. So it rotates with the automobile's wheel.

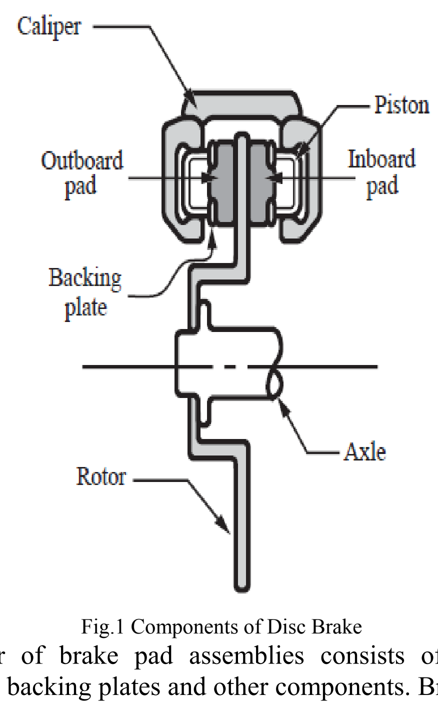


Fig.1 Components of Disc Brake

The pair of brake pad assemblies consists of friction material, backing plates and other components. Brake pads are pressed against the disc which generate a frictional torque to slow the disc(and wheel's) rotation. The caliper

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houses the hydraulic piston(s) which actuate the pad assemblies. When a driver depresses the brake pedal, there is increase in hydraulic pressure in the pistons housed inside the caliper. The device which converts the brake pedal's motion to hydraulic pressure is known as the master cylinder. It is connected by brake lines and hoses to the disc brake's caliper.

In majority of automotive disc brakes, the disc is made of grey cast iron. This material is wear resistant and inexpensive. In high performance disc brakes, the rotors are often slotted and/or drilled and are not necessarily composed of cast iron. The brake pad consists of a friction material which is mounted to a rigid pad backing plate. The mounting is achieved in a variety of manners, using rivets, using adhesives or integrally molding the friction material to the backing plate. These assemblies are mounted to the caliper or the caliper mounting bracket in various ways. It is common to use squeal prevention measures, usually in the form of dampers also known as shims or damping substances, in the contact regions between each of the pad backing plate and the caliper, and the caliper mounting bracket and piston(s).

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## 1.2 Classification of Disc Brake Squeal

Squeal has certain frequency. Brake squeal is also indicated by amplitudes of the vibrations of the brake disc in the micrometer range and the created sound pressure level (SPL). Depending on the various frequencies disc brake noise is classified in following categories.

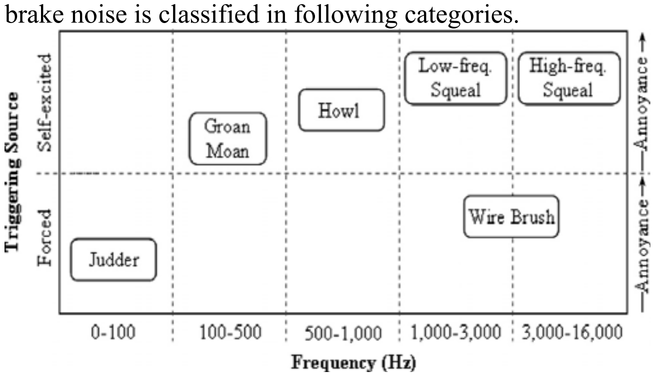

Fig.2 Classification of squeal

1. Low-frequency noise whose range is 100Hz to 1,000 Hz
2. Low-frequency squeals whose range is 1,000 Hz to 7,000 Hz
3. High-frequency squeals whose range is 8,000 Hz to 16,000 Hz

The main function of brake is to reduce the speed of vehicle. Brake squeal does not affect the main function of brakes. Although it does not affect the braking performance, it is not acceptable because of high frequency noise emissions. Brake squeal can occur in all types of friction-based brake systems, for disc brakes used in the aircraft, automotive, transport and motorcycle industry, drum brakes used in the automotive and motorcycle industry, block brakes of trains. There are different types of disc brakes, still, they apply the basic working principle: With an application of brake pressure to the brake piston, the brake pads makes frictional contact with the brake disc rotating at an angular velocity mounted rigidly on the vehicle axle.

## 1.3 Reasons/Causes of Disc Brake Squeal

Disc brake squeal occurs when there are very large mechanical amplitude in the braking system. There are two main theories that explain why this phenomenon occurs. The first theory is stick slip theory. This theory states that brake squeal is a result of a stick–slip mechanism. According to the second theory, high levels of vibration result from geometric instabilities of the brake system assembly. Both theories, results the brake system vibration and the audible noise are due to variable friction forces at the pad–rotor interface. According to the stick–slip theory, a variable friction coefficient with respect to sliding velocity between pads and rotor, gives the energy source for the squeal. Squeal noise was found to be more likely when the decreasing relationship between the friction coefficient and the sliding velocity become pronounced. According to geometric instability theory, even if the coefficient of friction is constant, variable friction forces are still possible. So the variable friction forces are caused by variable normal forces.

Also the condition for squeal generation is two system modes that are geometrically matched having about same frequency as the friction coefficient increases. These two modes couple at the same frequency and become unstable. When braking is applied, there may be occurrence of the frictional vibrations at the rotor–pad at a set of favorable conditions. The excitation generated induces modal response in the brake system, which is the source of squeal noise. This phenomenon is known as mode coupling mechanism.

The microscopic topography of contact surface has a strong influence on the generation of squeal. However, research is going on why squeal is generated in certain topographical conditions but vanishes in other conditions. Also scientists are studying how surface irregularities affect the generation of squeal. There is very limited information in the literature on the physical background of this phenomenon.

There is lots of study had been done in past years for disc brake squeal analysis. The researchers had considered the different parameters to study disc brake squeal. The parameters taken for testing had an influence over squeal generation. Various parameters namely pressure,

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temperature, coefficient of friction, rotational velocity, wear, various modifications in disc and pad have been studied by researchers to analyze disc brake squeal

## 2. Experimental Modal Analysis

The disc of a brake assembly can be tested through the EMA with free–free boundary conditions. The observational approaches to investigate the way patterns and natural frequencies of the any structure through impact hammer test. The most important part of the test system is the controller, or computer, which is the operator's communication link to the analyzer. It can be customized with various levels of memory, displays and data storage. The modal analysis software commonly used for analysis of structures for improved modifications.

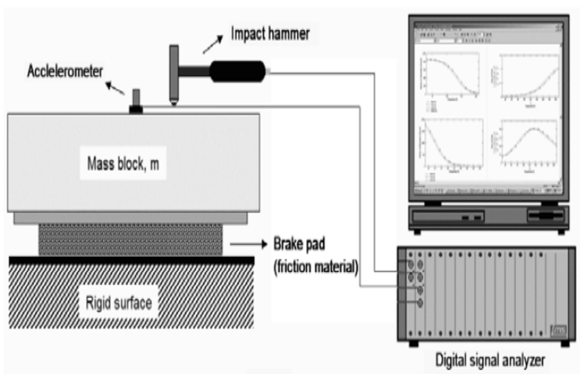


Fig.3 Experimental Modal Analysis Setup

The analyzer provides the data acquisition and signal processing operations. It can be configured with several input channels, for force and response measurements, and with one or more excitation sources for driving shakers. Measurement functions such as windowing, averaging and Fast Fourier Transforms (FFT) computation are usually processed within the analyzer.

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## 3. Application of the Finite Element Method in Brake Noise Analysis

In recent years, the finite element method has become an indispensable tool for modeling disc brake systems and providing new insights into the problem of brake squeal. This method provides a natural and straightforward means for generating finite dimensional approximations to the governing equations of motion for the components of the brake system. This is accomplished by admitting polynomial interpolations of the dependent variables (e.g., displacements and temperature) within each element sub domain. One view of the finite element method is that it

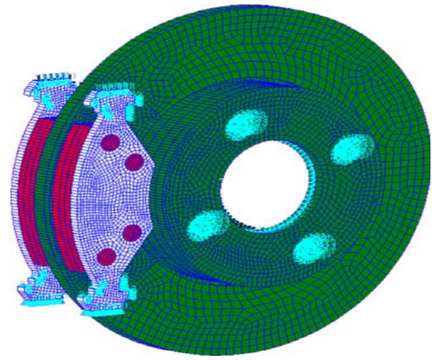

Fig.4 Finite element model of the disc brake system

has the capability of generating high-resolution finite dimensional models of form for a solid continuum. However, contrary to traditional lumped parameter techniques, the finite element method allows for accurate representation of complex geometries and boundary/loading conditions. Also, spatially resolved kinematic and kinetic quantities, such as strains and stresses, are readily computed as part of the finite element solution. Furthermore, the accuracy of a finite element model is typically controlled by the analyst, who may choose to refine the approximation in order to simulate the response of the brake system with a higher degree of fidelity.

The finite element method has been employed by researchers in brake squeal studies to several ends. One of its earlier uses was to investigate the modes and natural frequencies of the brake rotor. The most common use is to compute the M and K matrices in models of disc brakes. Subsequently, a linear eigenvalue analysis is conducted to determine the system's frequencies, modes, and stability. As in the other analyses we have cited, lack of (linear) stability, evidenced in the form of one or more non-dissipating eigenmodes is associated with squeal propensity.

## 4. Results and Discussion

### 4.1 Braking Pressure

Mario Triches Junior, Samir N.Y. Gerges, Roberto Jordan [1] studied relation between braking pressure and squeal occurrence. The effect of braking pressure was introduced into the finite element model with the variation of the contact stiffness between the rotor and pads. The use of the stress–strain relationship method to determine this contact stiffness, allows an evaluation of the effect of the braking pressure on the contact stiffness. The braking pressure has an important effect in terms of defining the main unstable frequency. Basically, increase in braking pressure leads to a linear increase in the main unstable frequency. In some cases, the braking pressure leads to some other unstable frequencies, such as a pressure of 75 psi. This result concluded that for a high braking pressure the frequency where the noise occurs tends to be higher.

Franck Renaud, Gael Chevallier, Jean-LucDion, Guillaume Taudiere [2] found that the accelerations measured showed that the squeal frequency was dependent on brake pressure. Many authors have studied the phenomenon of squeal noise on simplified test rig. In this paper a squeal noise experiment was performed on a real brake system. Six three-axis accelerometers were fixed on the backplate of the piston pad. The spectrum of the pad's acceleration presented a fundamental frequency and two harmonics during squeal noise occurrence. These harmonics highlighted the non-linear nature of the squeal noise phenomenon. As the squeal fundamental frequency was present almost throughout the experiment, there is occurrence of squeal noise only audible when the harmonics emerged. Here, squeal could not be result of a stick–slip phenomenon. The authors assume that the non-linear contact stiffness between pad and disc is a sufficient explanation for the harmonic rates observed. This assumption could be verified in future work by measuring the relative displacements between the pad and the other parts. The backplate motion of the piston pad was interpolated using the Finite Element method applied to acceleration measurements.

P. Liu, C. Cai, Y.Y. Wang, C. Lu, K.H. Ang, G.R. Liu [3] found that the effect of the hydraulic pressure on the squeal propensity. In this study pressure is varied from 0.5 MPa to 2.0 MPa.. The major squeal frequency found is approximately 12 kHz. It is also found that with an increase in pressure, the value of the damping ratio is increased, so the squeal probability is increased. This is because larger hydraulic pressure increases more friction between the pads and the disc. However, the simulation results show that the effect of the hydraulic pressure on the disc brake squeal is not much significant because the value of the damping ratio only changes from 0.17 to 0.193 when pressure increases from 0.5 MPa to 2.0 MPa.

## 4.2 Various Modifications in Disc and Pad

Yi Dai , Teik C. Lim [4] studied an enhanced dynamic finite element (FE) model with friction coupling is applied to study the design of disc brake pad structure for squeal noise. The FE model is developed from the individual brake component representations. The proposed friction coupling formulation model produces an asymmetric system stiffness matrix that gives a set of complex conjugate eigenvalues. From the analysis it is found that eigenvalues possessing positive real parts tend to produce unstable modes with the increased propensity of the generation of squeal noise. From the analysis beneficial pad design changes can be identified and implemented in the detailed FE model to find the potential improvements in the dynamic stability of the brake system. The best pad design attained, which produces the least amount of squeal response. It is finally validated by comparison to a set of actual vehicle test result.
The friction coupling and brake pad study gives the following specific conclusions:
1. Shorter lining reduces the propensity of squeal.
2.Higher coefficient of friction increases squeal occurrences.
3. Various contact angles of pin-disc are most susceptible to squeal.
4. Higher damping in the brake system tends to decrease squeal.
These design guidelines are then refined and used in the dynamic FE model to obtain a final pad design. The resultant design is then verified by using a set of vehicle level braking experiments.

D.W. Wang, J.L.Mo, H.Ouyang, G.X.Chen, M.H.Zhu, Z.R.Zhou [5] studied an experimental and numerical study of friction-induced vibration and noise of a system. In experimental study an elastic ball sliding over a groove-textured surface was used. Results obtained from experimentation showed that the contact between the ball and the edges of the grooves highly reduce the generation of high frequency components of acceleration and reduce the friction noise. Groove-textured surfaces with a specific predefined dimensional parameter showed interesting characteristics in reducing squeal. To model and study this noise phenomenon, both the complex eigenvalue and dynamic transient analysis were performed.
Results and conclusions from both the experimental and numerical can be made as follows:
1. Groove-textured surfaces with a specific dimensional parameter showed good characteristics in reducing and suppressing squeal in the experimental test. This is because impact behavior between the ball and the edge of the groove-textured surface reduces the self-excited vibration of the friction system, and lowers the probability of generation of high frequency components of the acceleration.
2. The numerical model generated in this work can be effectively used to explain the effect of groove-textured surface on the friction, vibration and noise. The dynamic transient analysis for the cases of groove-textured surface further validates the role of impact between the ball and the groove edges. It shows that the existence of impact would reduce the self-excited vibration of the friction system and suppress generation of squeal.

Franck Renaud, Gael Chevallier, Jean-LucDion, Guillaume Taudiere, [2] studied the operating deflection shape of a pad during squeal noise. It is measured on a real brake system with three-axis accelerometers. A time-frequency analysis is performed that showed generation of squeal on the hydraulic pressure of the system and shows that squeal occurs simultaneously with harmonic components. The operating deflection shape of this pad before and during squeal is then visualized using interpolation, showing the predominance of bending motion. In the end, the pad motions observed are compared to the real modal basis of a detailed Finite Element model.

Toru Matsushima, Kazuhiro Izui, Shinji Nishiwaki [6] in this paper there is modifications in brake components is studied. Disc brake squeal occurs due to the changes in unpredictable factors such as the friction coefficient, contact stiffness, and pressure distribution along the contact surfaces of the brake disk and brake pads. Author proposes a conceptual design method for disk brake systems that aims to reduce the occurrence of low frequency brake squeal at frequencies below 5 kHz.This is done by modifying the shapes of brake system components to obtain designs that are robust against changes in the above unpredictable factors. A design example is provided and the optimal solutions are validated using real-world experiments.

S. Oberst, J.C.S. Lai, S. Marburg [7] demonstrated that contact separation as observed experimentally and in analytical/numerical models is possible and could result in impact excitation of the rotor by the pad and an acoustic horn effect. It was found that for a simplified brake model using an annular disc, with a chamfered pad having reduced contact area is used in industries to reduce instabilities have an adverse effect on the acoustic radiation of a brake system. This study shows the importance of acoustic radiation as illustrated by the horn effect arising from chamfered pads and the importance of developing a proper understanding of contact dynamics including a realistic friction model.

J.L. Moa, Z.G.Wanga, G.X.Chen, T.M.Shao, M.H.Zhu, Z.R.Zhou [8] studied an experimental study on the effect of groove-textured surface on tribological behaviors and friction-induced vibration and noise properties. Groove-textured surfaces with different widths and pitches were manufactured on compacted graphite iron materials by electro machining. The difference between the groove-textured and original smooth surfaces in friction, wear, vibration and noise properties was studied, by using a developed device which is able to measure and analyze the friction force, vibration, acceleration and noise signals in a ball- on-flat reciprocating sliding surface.

Conclusions obtained from the experimental results,

1. The squeal generated from the groove-textured surface was mainly affected by the dimensional proportion of groove width to pitch. In this work, groove-textured surfaces having specific dimensional proportion of groove width to pitch of 1/2 can effectively reduce squeal.
2. The squeal in this work was mainly caused by the local dynamics at the contact surface which excited a mode of the tribosystem.
3. There is no correlation between the value of friction coefficient and the generation of squeal. Squeal was found to occur associated with significant continuous high-frequency fluctuations of friction force and vibration accelerations. These fluctuations were mainly caused by the microscopic irregularities of the worn surface, wear debris layer and detachment. Groove-textured surface with specific geometry allowed an easier wear debris escape from the contact zones into the grooves, which would help to reduce the irregularities and consequently the squeal tendencies.

Gottfried Spelsberg-Korspeter [9] showed analytically and experimentally that the stiffness properties of the disc are important. Splitting of double modes of the disc has a stabilizing effect. This knowledge is useful for structural optimization of brake rotors. Author explained experimental evidence for the relation of rotor asymmetry and squeal. It is shown that every elastic body with a cyclic symmetry with an angle less than Ω has at least one double eigen frequency. It makes susceptible to self-excited vibrations, when operated as a rotor in frictional contact.

## 4.3 Velocity

Choe-Yung Teoh, Zaidi Mohd Ripin, Muhammad Najib Abdul Hamid [10] studied that low sliding velocity is responsible for occurrence of squeal. Because low velocity is able to excite limit cycle of large amplitude vibration due to the alternately varying direction of friction forces. As coefficient of friction increases there is decrease in the critical value of sliding velocity. The increase in the braking load increases the critical value of sliding velocity and affects the limit cycle of the vibration.

P. Liu, C. Cai, Y.Y. Wang, C. Lu, K.H. Ang, G.R. Liu [3] found that as the angular velocity increases, the value of the damping ratio gradually decreases. However, when there is change in the hydraulic pressure, the effect of changing the angular velocity on the squeal propensity is also not obvious. This shows the value of the damping ratio varies with an increase in the rotational velocity of the disc.

### 4.4 Coefficient of Friction

Choe-Yung Teoh, Zaidi Mohd Ripin, Muhammad Najib Abdul Hamid [10] has been developed a nonlinear two degree-of-freedom model of a drum brake system and verified experimentally. Transient analysis was carried out which showed that binary flutter mechanism increases with friction coefficient and dependant on the location of center of pressure. Squeal can be eliminated or reduced by design alterations of mode separation, increase of system damping and reduction of contact stiffness for coefficient of friction range of 0.1-0.5.

P. Liu, C. Cai, Y.Y. Wang, C. Lu, K.H. Ang, G.R. Liu [3] explained that disc squeal is to be caused mainly by friction-induced dynamic instability. Authors studied the variations in coefficient of friction within range 0.2-0.8 and effect of variance in coefficient of friction on contact interactions of disc and pad. Results are in the form of the damping ratio as a function of frequency for different friction coefficients. It is observed that the major squeal frequency is approximately 12 kHz. The value of the damping ratio is decreased with a decrease of the coefficient of friction. It is also observed that with an increase in the friction coefficient, there is an accompanying increase in the instability of the system, thus an increase in the damping ratios. This shows that the squeal can be eliminated by reducing coefficient of friction between the pads and the disc. But, this obviously reduces braking performance and is not a preferable method to apply.

### 4.5 Damping

A. Akay, O.Giannini, F.Massi, A.Sestieri [11] studied three simplified test rigs ,that are, the beam on disc, the laboratory brake, and the tribobrake COLRIS. All the numerical and experimental results related to the test rigs agree and can be observed to show that squeal is a dynamic instability driven by three factors:
1. The friction force is responsible for inducing asymmetry in the stiffness matrix. This is a characteristic exhibited by any friction law because friction couples together normal and tangential forces.
2. The increase of damping of the coalescing modes may increase the frequency range for which such has $90^\circ$ phase shift occurs, so that squeal can be suppressed, leading to a wide run stable range.
3. The role of damping cannot be neglected. Because it has experimental evidence that one can predict the presence of squeal in the braking system if damping is neglected.

Choe-Yung Teoh, Zaidi Mohd Ripin, Muhammad Najib Abdul Hamid [10] studied drum brake squeal is modeled as friction excited vibration based on the binary flutter mechanism. Increase in damping can be applied to reduce the amplitude of the limit cycle of the drum brake squeal.

Hugo Festjens, Chevallier Gael , Renaud Franck, Dion Jean-Luc, Lemaire Remy [12] studied the actual role of multi-layered viscoelastic parts, called as shims, to prevent squeal noises of automotive brake systems. Shear stress is usually used to damp thin structures in their bending modes it is believed to be the largest underwent by shims. To crosscheck this assumption and considering that stresses underwent by shims cannot be measured experimentally, the authors have computed them with the help of a detailed and realistic finite element model. Opposite to what shims manufacturers say, this study explains the fact that shims are almost uniquely solicited in their normal direction in brake systems. Also the study focuses on the effect of added damping and stiffening induced by the viscoelastic materials. Finally, the study shows certain Eigen modes for which the viscoelastic behavior of the shims explains instabilities that would not exist without damping shims

## 5. Conclusion

In this study various parameters affecting disc brake squeal are studied. Effect of increasing braking pressure leads to increase in disc brake squeal. It is found that lower rotational velocities have more probability to occur disc brake squeal. Higher coefficient of friction increase squeal propensity. Increase in damping reduces disc brake squeal.
For elimination or reduction of disc brake squeal most important parameter is structural modifications in brake pad and disc. Because From literature, it is found that braking pressure and velocity are dynamic parameters. Coefficient of friction cannot be reduced under certain limit as it affects braking performance. Additional damping reduces squeal propensity but it adds more cost to brake system. Structural modifications in disc and pad influence the disc brake squeal. So design modifications in braking system mostly disc and brake pad will save additional cost of damping. Also there is no requirement of lower coefficient of friction if structural modifications done, there will be higher braking performance. This study will be useful for further research work.

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