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Review

Motor Vehicle Brake Pad Wear—A Review

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Abstract: The paper offers an overview of the motor vehicle brake pad wear process. Considering the types of wear that occur between the pads and the disc, the study begins by presenting Archard's fundamental wear law. It explains how the hardness and roughness of materials can influence the wear rate. Furthermore, the analysis describes factors influencing the wear coefficient, including chemical affinity between materials, surface quality, thermo-elastic instability (TEI) of the materials, and environmental effects. The paper also presents detection systems for brake pad wear, such as sensors-based monitoring and artificial neural networks (ANNs). These systems monitor brake pad wear in real time, thereby improving the driving safety by alerting the driver to the condition of the brake pads. The principles and systems analyzed form the basis for predictive maintenance, minimizing the risks of brake failure due to excessive wear.

Keywords: brake pad wear; wear mechanisms; Archard's wear law; thermo-elastic instability; chemical affinity; surface quality; sensor-based monitoring; artificial neural networks

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1. Introduction

The braking system is one of the most important components of a motor vehicle, where factors such as safety, performance, and environmental impact are critical. Brake pad wear significantly influences braking effectiveness. As brake pads wear, friction diminishes, leading to longer stopping distances and an increased risk of accidents [1–3]. Researchers have shown that when the thickness of brake pads falls below a certain threshold, braking efficiency is compromised, posing a safety hazard [1,4]. Studying the brake pad wear phenomena of brake pads has led to the development of new designs and improved materials. In fact, studies have demonstrated that the wear characteristics of pad materials vary with parameters such as temperature and load [5–7]. As illustrated in Figure 1, multiple mechanisms act concurrently during the wear process—including abrasion, thermal degradation, and chemical reactions—to varying degrees depending on the pad material properties [5,8]. Initially, asbestos-based materials were used, but these were later found to pose serious health risks. Alternative materials, such as those containing a low quantity of copper, have been developed to improve performance and reduce health hazards [6,8]. During braking, the resulting particles contribute to air pollution. Ismailov et al. quantified emissions from the brake pad wear, highlighting the need to reduce wear debris [9].

Due to growing regulatory and environmental demands related to motor vehicle emissions, the study of brake pad wear has become an area of increasing interest. Real-time wear monitoring systems, employing advanced sensing technologies, have been developed to predict when brake pads replacement is needed, alerting drivers accordingly [1,2].

The schematic figures included for each chapter serve as visual guides to the article's thematic structure and referenced literature. Each diagram places the chapter's main topic at the center (orange), with key categories branching out (blue) and individual cited studies shown as article nodes (green). This layout is designed to support readers in two key ways: first, by simplifying the conceptual flow of the review; and second, by allowing readers to quickly identify which references relate to which subtopics. This is especially useful in a review article, where the goal is often to locate relevant literature for a particular aspect of a broader topic. By scanning the figures, readers can efficiently navigate the review and directly target the sources most relevant to their interests or research needs. For example, in Figure 1, "Brake Pad Wear" is the central node. Surrounding it are major themes such as safety, performance, environmental impact, material evolution and monitoring systems. Under safety, for example, the graph shows two linked article nodes: "stopping distance" and "accident risk". Every article node has a number that can be found in the caption with the articles mentioned in References. The mentioned articles from node (1) and (2) like [1–4] focus on the safety consequences of brake pad wear. Thus, a reader interested in safety-related studies can immediately focus on those references without reading the entire text. This method streamlines literature discovery, allowing the figure to act as a reference map that complements the narrative discussion in the review.

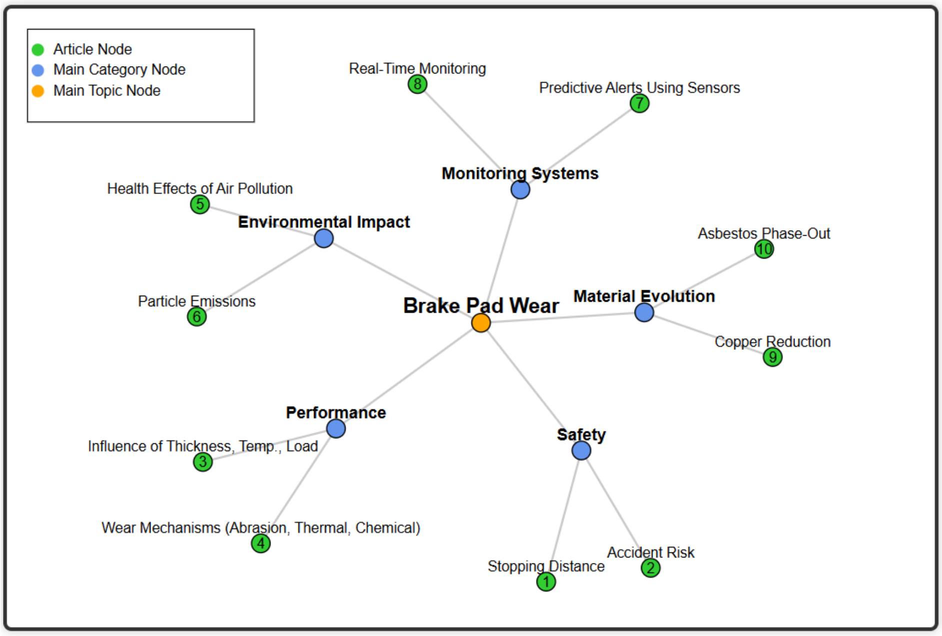

Figure 1. Overview of the mechanisms contributing to brake pad wear. Article node: (1)–[1–3], (2)–[1,4], (3)–[5–7], (4)–[5,8], (5)–[6,8,9], (6)–[9], (7)–[1,2], (8)–[1,2], (9)–[6,8], (10)–[6,8].

2. Types of Wear on Brake Pads

To enhance safety, optimize maintenance schedules and improve the brake design, it is necessary to understand the complexity of the wear process. The primary wear mechanism is "abrasive wear", which occurs due to the mechanical interaction between the brake pads and the disc during braking. It is characterized by the removal of material from the brake pad due to the sliding friction. Several influence factors, such as the pad's material composition, the characteristics of the friction layer between pad and the disc, and the braking conditions, contribute to this wear [3,10]. The presence of hard particles in the brake pad can increase wear, leading to a higher material loss [1].

Another significant wear type is "adhesive wear". It occurs when the materials of pads and the disc bond at contact surface at high temperature and pressure regimes. This wear consists of a material transfer from one surface to another, creating an uneven wear pattern and wear debris formation. At high sliding speeds and heavy loads conditions, the thermal loads will cause localized melting points and material transfer [3].

"Thermal wear" is a process in which high temperatures weaken the brake pad material. Changes in thermal properties, such as thermal conductivity and the ability of the material to dissipate heat, can occur [11]. Due to high temperatures, cracks may appear on the surface, further contributing to brake pad wear [3,11].

"Partial wear" is another phenomenon caused by an uneven contact between pads and the disc. This uneven contact, which can arise from misalignment or an uneven distribution of braking force, leads to localized wear patterns. As a result, the braking efficiency and the lifespan of the pads are adversely affected, highlighting the need for careful monitoring and maintenance [12]. Each wear type—abrasive, adhesive, thermal and partial—is influenced by factors like material properties, mechanical interactions and braking conditions. As shown in Figure 2, these mechanisms often occur concurrently during the braking process, underscoring the complexity of wear phenomena. Understanding these wear mechanisms is vital for developing effective brakes that enhance vehicle safety and reduce negative impacts on human health.

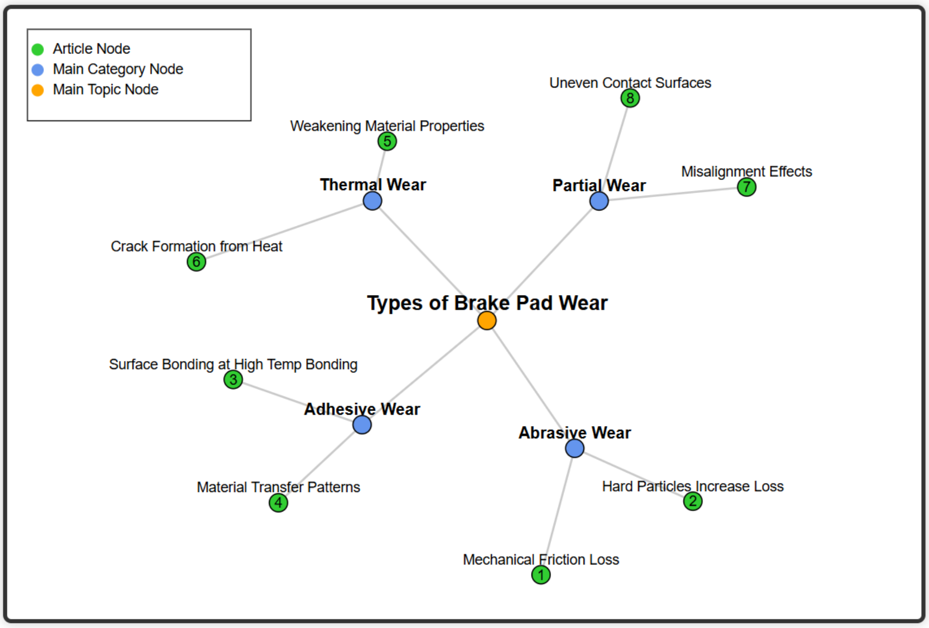

Figure 2. Schematic representation of the main wear mechanisms on brake pads. Article node: (1)–[3,10], (2)–[1], (3)–[3], (4)–[3], (5)–[11], (6)–[3,11], (7)–[12], (8)–[12].

3. Mathematical Analysis of Brake Pad Wear

3.1. Archard's Law

To predict brake pad wear, mathematical models play a significant role by allowing the estimation of wear rates and service life under various operating conditions. Several approaches quantify brake pad wear based on factors such as material properties, pressure, and temperature. The most common model is Archard's wear law, which provides a fundamental equation to estimate the wear volume based on the applied load, material-specific wear coefficient and the sliding distance. This equation is expressed as

$$V = \frac{k \cdot F \cdot d}{H}, \tag{1}$$

where V is the total volume of the wear debris produced, k is a dimensionless constant (Archard's wear coefficient), F is the normal load, d is the sliding distance, and H is the material hardness [13]. This model clearly illustrates the influence of the load and sliding distance on wear rates.

3.2. Wear Calculation Models

Archard's law has limitations when applied to brake pad wear analysis. For this reason, several studies have developed alternative models that account for variations in parameters under different braking conditions. Given the complexity of the braking phenomenon, variables such as speed, temperature and load must be analyzed in greater detail. While Archard's law describes a linear relationship with wear, empirical nonlinear models have also been proposed [14]. In these empirical models, wear volume is expressed as a function of normal load F, sliding speed v, and time t, with each factor having an exponential influence [15,16]:

$$V = k \cdot F^a \cdot v^b \cdot t^c, \tag{2}$$

The exponents a, b, and c are specific to the friction material and the environmental conditions. For commercial friction materials a = 0.42 [15], while for metallic pads, the normal load exponent has been found to be approximately 0.62 $\pm$ 0.02 [17]. This model is particularly relevant in nano-scale wear analysis under varying loads, where Archard's linear formulation is insufficient. However, a key limitation is that it does account for temperature variation. To address this, Hohmann et al. developed a wear model based on experimental data that incorporates pressure P, temperature T, thermal capacity of the material c, sliding time t, and an apparent contact area A [18].

$$V = \sum (c_{ij} \cdot P^i \cdot T^j) \cdot \frac{t}{A}, \tag{3}$$

This formulation is particularly useful for finite element analysis when studying the effects of wear on noise and vibration in braking systems [16,19]. A more data-driven approach involves multiple linear regression (MLR), a statistical technique that relates wear (the dependent variable) to multiple independent variables such as speed, pressure, and time [20–22]:

$$V = a + b \cdot X_1 + c \cdot X_2 + d \cdot X_3 + \cdots + \varepsilon, \tag{4}$$

Here, X_1, X_2, X_3 are independent variables. a, b, c, d are regression coefficients determined experimentally, and ϵ represents model error. Other researchers have proposed wear estimation methods based on vehicle dynamics. Hwang proposed a model to estimate the brake pad wear using dynamic data such as wheel speed, vertical acceleration, and disc temperature [23]. This model offers a practical method for real-time wear estimation in vehicles. More complex analyses use longitudinal dynamic models that consider six elements: inertia, engine force, friction brakes, aerodynamic drag, rolling resistance, and gravity. Vehicle motion states—such as stationary, coasting, engine braking, propulsion, and friction braking—can be inferred from data collected via the vehicle's CAN system during extended driving. By combining this approach with friction coefficient measurements from the pin-on-disc method, it is possible to more accurately estimate the Archard wear coefficient [24,25]. These alternative models emphasize the complexity of brake pad wear, which is influenced by a wide range of factors that vary with climate, driving style, load, and geography. Nonetheless, Archard's law remains a useful starting point, especially in controlled laboratory conditions, providing predictive insights, despite its limitations in accuracy capturing wear behavior under real-world conditions.

3.3. Artificial Neural Networks (ANNs)

Artificial neural networks (ANNs) have also been employed to model wear behavior, capturing complex relationships between braking parameters and wear outcomes. ANNs are mathematical models inspired by the human brain: neurons are arranged in layers and interconnected by weighted links, enabling the network to learn complex relations from example data. A typical ANN comprises an input layer receiving (load, speed, pressure, temperature, material characteristics etc.), one or more hidden layers (performing nonlinear transformations), and an output layer (producing estimated brake pad wear). Different algorithms can be used within the hidden layers to optimize predictions. Feedforward neural networks (FNNs) represent the simplest ANN architecture, consisting of an input layer, hidden layer(s), and are typically trained using backpropagation. While FNNs can estimate brake pad wear, insufficient neurons or layers can lead to overfitting [26]. Multilayer perceptrons (MLPs) extend FNNs by incorporating multiple hidden layers with various activation functions. MLPs are effective at modeling complex, nonlinear wear phenomena but require large datasets and substantial computational resources [27]. Recurrent architectures—particularly long short-term memory (LSTM) networks—excel at capturing temporal dependencies in sequential braking data, enabling wear prediction over time; however, they demand significant computational power and extensive sequential datasets [1]. Convolutional neural networks (CNNs), traditionally used for spatial data and image analysis, can extract wear patterns from pad surfaces. When combined with LSTM layers into hybrid CNN-LSTM models, they jointly capture spatial and temporary aspects or wear progression [1,28]. Such hybrids improve accuracy but require careful validation to avoid overfitting. To further enhance ANNs performance, evolutionary algorithms (e.g., genetic algorithms and particle swarm optimization) have been applied to determine the optimal neuron counts and layer configurations. These methods can significantly improve predictive accuracy but incur additional computational cost [29]. Selecting and combining appropriate ANNs architectures is critical, as ANNs generally offer higher predictive accuracy than traditional models across diverse scenarios [2,30].

As shown in Figure 3, these diverse mathematical models collectively offer a comprehensive framework for predicting brake pad wear under various operating conditions. Together, analyses based on Archard's law, ANNs, and statistical approaches have led to the development of new equations and models essential for predicting service life and understanding the influencing factors of brake pad wear.

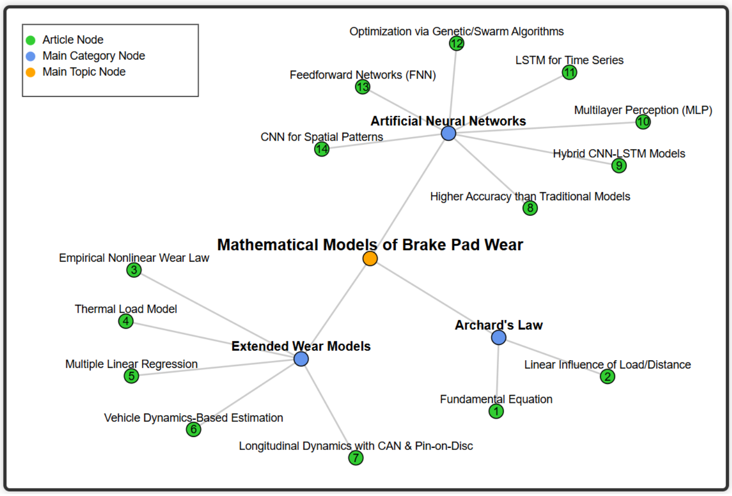

Figure 3. Mathematical models for brake pad wear prediction. Article node: (1)–[13], (2)–[13], (3)–[14–16], (4)–[18], (5)–[20–22], (6)–[23], (7)–[24,25], (8)–[2,30], (9)–[1,28], (10)–[27], (11)–[1], (12)–[29], (13)–[26], (14)–[1].

4. Influence Factors of the Wear Coefficient

The wear coefficient in Archard's law is influenced by the type of brake pad material, composition, and operating conditions. The composition of the pad materials affects the hardness of the brake pads. According to Archard's law, the wear volume is inversely proportional to the material hardness. In other words, as hardness increases, the wear volume decreases, suggesting that harder materials tend to exhibit lower wear rates [31]. Moreover, harder materials often display higher thermal stability and a lower wear coefficient because they can withstand higher temperatures and loads without significant degradation [13].

Conversely, softer materials wear more quickly under similar conditions, resulting in a higher wear coefficient [32].

Material composition is critical. Organic binders such as phenolic resins, when combined with various fillers exhibit different wear characteristics compared to metallic or ceramic composites. Nandiyanto found that brake pads with higher phenolic resin content have improved wear resistance due to enhanced thermal and mechanical properties [33]. The cross-linked structures of phenolic resins promote heat transfer throughout the pad reducing overheating and brake fade, thereby extending pad life [34]. In contrast, pads containing metallic fibers may provide a higher friction coefficient but can also lead to increased wear rates due to their abrasive nature [35]. They also ensure a good heat transfer, especially if the fillers are aluminum or aluminum oxide (Al_2O_3) [36,37]. Temperature also affects friction and wear. Oktem et al. showed that, at a constant disc speed, the friction coefficient decreases from 0.45 at 100 °C to 0.28 at 350 °C, while the specific wear rate increases from 1.13×10^{-7} N · m · cm^{-3} to 103×10^{-7} N · m · cm^{-3} under 100 braking cycles at 800 rev · min^{-1} [38]. Adding petroleum coke as a friction modifier, further stabilizes the friction coefficient and reduces wear [38]. Studies of composite pads reinforced with fibers—such as rockwool, ceramic, E-glass and steel wool—indicate that the friction coefficient decreases with the increased load and speed but rises with temperature up to 300 °C; prolonged braking further increases wear, with E-glass and steel wool fibers exhibiting the highest wear rates [39,40]. No direct correlation was observed between wear rate and applied load in these tests. Operating conditions such as load and temperature—shaped by driving style and road terrain—can account for nearly half of the wear rate variation with load alone contributing up to 48.07% [10,41]. Minor factors, including contaminants, moisture, and variations in surface roughness, can also alter frictional properties and thus modify the wear coefficient.

4.1. The Thermo-Elastic Instability (TEI) Phenomenon

The thermo-elastic instability (TEI) phenomenon arises from the combined effect of mechanical and thermal stress, particularly during intensive braking at high speeds. This phenomenon affects the wear coefficient in Archard's law, by creating instabilities that lead to uneven wear patterns due to the formation of hot spots. During braking, mechanical energy is converted into heat. When temperatures exceed critical thresholds, TEI is initiated, resulting in changes to the brake pad material properties—specifically, a reduction in hardness and an increase in wear. Archard's law implies that a decrease in hardness (H) leads to an increase in wear volume (V) for a given load (F) and sliding distance (S) [42,43].

TEI causes the localized heating and deformation of the brake pad surface, resulting in hot spots [44]. These hot spots reduce the effective contact area between the disc and brake pads, leading to higher localized pressures and, consequently, an increased wear coefficient in those regions [45]. The local strain induced by these hot spots can further intensify wear in a feedback loop. Moreover, TEI alters the friction coefficient between the brake disc and the pads. The resulting non-uniform temperature distribution makes friction behavior unpredictable. Initially, the friction coefficient may rise with temperature—thereby reducing wear—but beyond a certain point, increased thermal loading leads to higher overall wear [46,47].

Different brake pad materials respond variably to thermal stress. Materials with high thermal conductivity dissipate heat more effectively, mitigating TEI effects and resulting in a more stable wear coefficient. In contrast, materials with lower thermal stability exhibit a more pronounced increase in the wear coefficient under thermal cycling [43,47].

Shirsath et al. conducted a thermo-mechanical analysis of various non-asbestos organic (NAO)-based friction materials and demonstrated that NAO materials exhibited lower stress (less than 30–45%) and deformation (less than 22%) compared to conventional materials. Moreover, these materials maintained a lower holding temperature relative to metal-based friction composites, which experienced higher stress, heat flux, and deformation [48].

Given the variability in braking conditions—such as differences in speed and load—the relationship between wear coefficient and TEI is complex. Rapid changes in brake conditions can cause temperature spikes that exacerbate TEI, resulting in unpredictable wear patterns that are challenging to model accurately using Archard's law, where material properties are assumed to be constant [49,50].

4.2. Surface Quality

The wear rate is influenced by the quality of the surface, including roughness, texture and the presence of contaminants. A smoother surface generally results in reduced abrasive interactions between the disc and the pads. However, as brake pads wear, the surface may become rougher, which can increase abrasive wear. Initially, smoother surfaces may yield lower friction, but as wear develops and roughness increases, braking efficiency can improve up to a certain point [51].

During braking, a tribofilm forms on the surface of both the disc and the pads due to wear debris. The tribofilm alters the surface characteristics, reducing both wear and friction. Laguna-Camacho et al. demonstrated that repeated braking alters surface morphology, affecting tribofilm formation, and consequently, the overall wear behavior. A stable tribofilm can act as a protective layer, reducing the wear rate [5].

Scanning electron microscope (SEM) analysis of friction surfaces often reveals irregularities, such as micro-holes, which are formed when non-metallic components rapidly cool down upon contact with metallic parts. The accumulation of wear particles in these irregularities may further increase the friction coefficient [52].

In addition, contaminants like dust, moisture, or oily residues can affect the surface properties of disc and brake pads. Majuma et al. found that extending braking in challenging terrains can lead to increased wear rates due to the thermal degradation of the brake pad material, exacerbated by airborne contaminants [41]. Moreover, humidity can influence the adhesion of the wear debris to the surfaces, potentially stabilizing the friction coefficient while also increasing the wear under certain conditions [53].

The overall state of the friction surface directly impacts the friction coefficient. As Yavuz and Bayrakceken demonstrated, irregular friction surfaces tend to increase wear rates due to the instability of the friction coefficient [54] which may induce additional thermal loads and further accelerate wear.

4.3. Chemical Affinity Between Disc and Pad Surfaces

Chemical affinity between disc and pad surfaces refers to the extent to which materials form chemical bonds upon contact, thereby influencing frictional interactions, wear debris formation, and adhesion. During braking, abrasive wear is caused by the exfoliation of wear particles, which are released into the atmosphere. In contrast, adhesive wear occurs when material transfers between components due to strong bonding forces at the contact surfaces. This material transfer can alter the friction characteristics between the disc and the pads, giving rise to a stick–slip phenomenon. Under load, material transfer between the contacting surfaces can cause fluctuations in both the static and dynamic friction coefficients, with average variations of 1.55% and 1.29%, respectively, resulting in vibrations with an average of amplitude of 9.46% [55].

The composition of a brake pad, which includes fibers, fillers, and binders, significantly affects the friction coefficient through its influence in the interaction between the pad and the disc surfaces. The inclusion of additives, such as solid lubricants, may enhance friction stability and reduce wear by forming protective layers [56]. Conversely, a high copper content in brake pads can increase adhesive wear when used with certain disc materials [41].

Incompatible materials tend to increase friction, thereby generating excess heat that further degrades the material. Josan Ana et al. investigated the alloying of brake disc materials and found that varying concentrations of copper and molybdenum result in distinct microstructural features—such as punctiform interdendritic graphite—which improve heat transfer and increase hardness [57], ultimately reducing thermal stress on the brake mechanism.

Additionally, the formation of a tribofilm can mitigate pad wear. The presence of graphite or other lubricants helps form a beneficial tribofilm that reduces wear [35]. However, if the tribofilm becomes unstable or if abrasive particles are present, the wear rate will increase as fresh material is continuously exposed to the wear process.

High braking temperatures can also trigger chemical reactions between components—especially affecting organic materials—which may degrade and contribute to increased wear [58].

Environmental factors, such as humidity or contaminants can facilitate the chemical reactions, leading to corrosion and additional wear [59,60]. Figure 4 shows a schematic representation of the main factors that can influence brake pad wear.

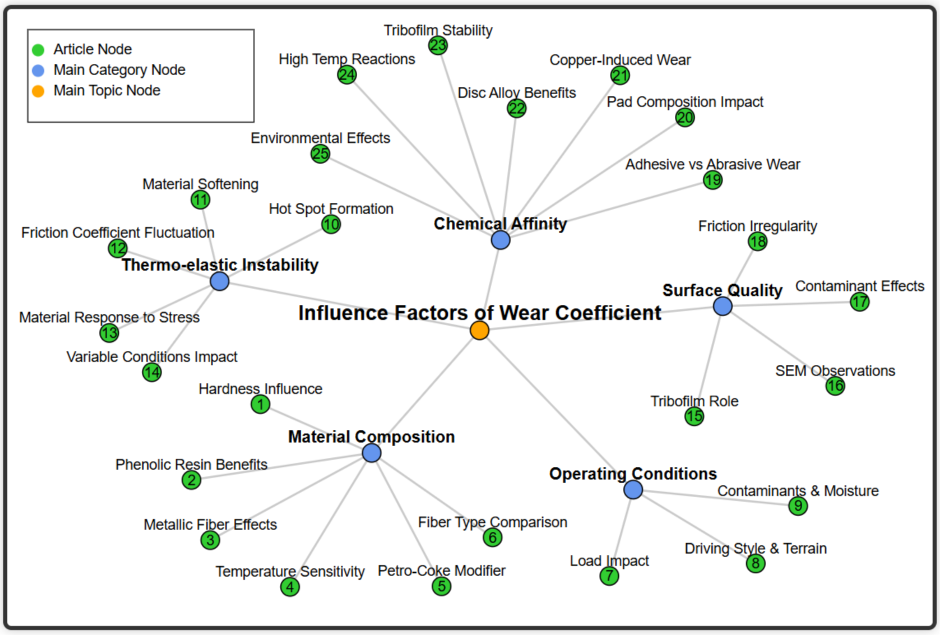

Figure 4. Influencing factors on brake pad wear. Article node: (1)–[13,31], (2)–[33,34], (3)–[35–37], (4)–[38], (5)–[38], (6)–[39,40], (7)–[10], (8)–[41], (9)–[41], (10)–[44], (11)–[42,43], (12)–[46,47], (13)–[48], (14)–[49,50], (15)–[5,51], (16)–[52], (17)–[41,53], (18)–[54], (19)–[55], (20)–[56], (21)–[41], (22)–[57], (23)–[35], (24)–[58], (25)–[59,60].

5. Wear Detection and Prediction Systems

Determining the actual brake pad wear involves a variety of physical tests, primarily conducted in laboratory settings. One common method is the "pin-on-disc" test, where a pin representing the brake pad is pressed against a rotating disc under controlled conditions. This test evaluates the tribological behavior of the materials, allowing for the measurement of wear rates and friction coefficient [6,8,52,57]. Another widely used test is the "inertia dynamometer", which simulates real-world operating conditions. On the test bench, various parameters such as speed, load, and braking patterns can be replicated to perform further analysis—such as thermo-mechanical evaluations—mimicking actual vehicle operation [58,61,62]. Additionally, the "weight loss measurement" technique, which involves weighing the pads before and after testing, to determine mass loss, is commonly employed [62,63]. In practical applications, vehicles are equipped with systems that notify users of the brake condition. Many motor vehicles incorporate monitoring systems that use sensors to measure the thickness of the brake pads. These systems, usually employing gap sensors, trigger alerts when the pad thickness reaches a critical level, thereby indicating the need for replacement [1]. Other systems use vibroacoustic sensors to capture changes in the acoustic signature during braking—providing indirect feedback on wear. Similarly, thermal imaging and temperature sensors, typically used in high-performance vehicles, detect excessive wear or component malfunction based on elevated temperatures [64]. Advanced techniques such as artificial neural networks have been utilized to predict brake pad wear.

By training on experimental data, ANNs in these systems can forecast wear based on braking conditions, speed, and load, as demonstrated by Yin et al. [65]. Using pin-on-disc with increasing load, contact time, and sliding speed made possible to highlight the increased wear rate—not only through direct measurement, but also using ANNs with a two-layer model in MATLAB [30]. ANN models can be a reliable approach for predicting surface parameters, friction, and wear, as test results have shown agreement simulation [66]. Vasiljević et al. have demonstrated how neural networks can forecast the wear rate by considering mechanical aspects of operation, such as applied load and sliding distance [27]. Given the complexity of the braking process—due to its dynamic nature, including intensive, repeated, and prolonged braking throughout the entire brake pad life cycle—ANNs can estimate material wear rate. A back-propagation ANN model that integrates multiple operational parameters can be used to predict the wear life of the brake pads. Cao et al. demonstrated the value of ANNs in establishing a comprehensive understanding of the wear process under different conditions [2]. The brake pad typically contains more than 20 different ingredients resulting in complex tribological interactions that influence the characteristics of the friction materials used in pad linings. Aleksendrić developed a neural model of brake wear prediction using 15 different neuronal networks and 5 training algorithms generating a total of 75 neuronal models [67]. Kuncy et al. used ANN to predict friction coefficient and wear in brake pads made from palm kernel fibers, highlighting the adaptability of the method across different material formulations [68]. Using an ANN trained on data collected from a custom built braking test rig, a forecasting model was developed. This braking tester simulated conditions more closely aligned with real-world braking than standard pin-on-disc tester. Based on this, an online brake wear monitoring system was designed [65]. The formulation and manufacturing process of the brake linings can also influence the brake pad wear. Han et al. analyzed 16 influencing factors as input and wear rate as output. In the hidden layer of the ANN model, they used the Levenberg–Marquardt algorithm to predict wear properties and optimize both formulation and manufacturing conditions [69]. Real-time wear estimation can also be achieved using fuzzy logic systems. Fahruzi proposed a fuzzy logic-based method for estimating brake pads wear initially using three main parameters: vehicle speed, brake fluid pressure, and brake duration. Tests were conducted on a bench, simulating braking conditions for a two-wheel vehicle, where the pad's wear was monitored. Over a 30 min period with two pressure values, measured wear values supported the fuzzy system's reliability for real-time estimation [63].

Figure 5 illustrates an array of detection and prediction systems, which collectively provide a robust framework for monitoring brake pad wear under both laboratory and real-world conditions, facilitating timely maintenance, and thereby helping to prevent brake failures.

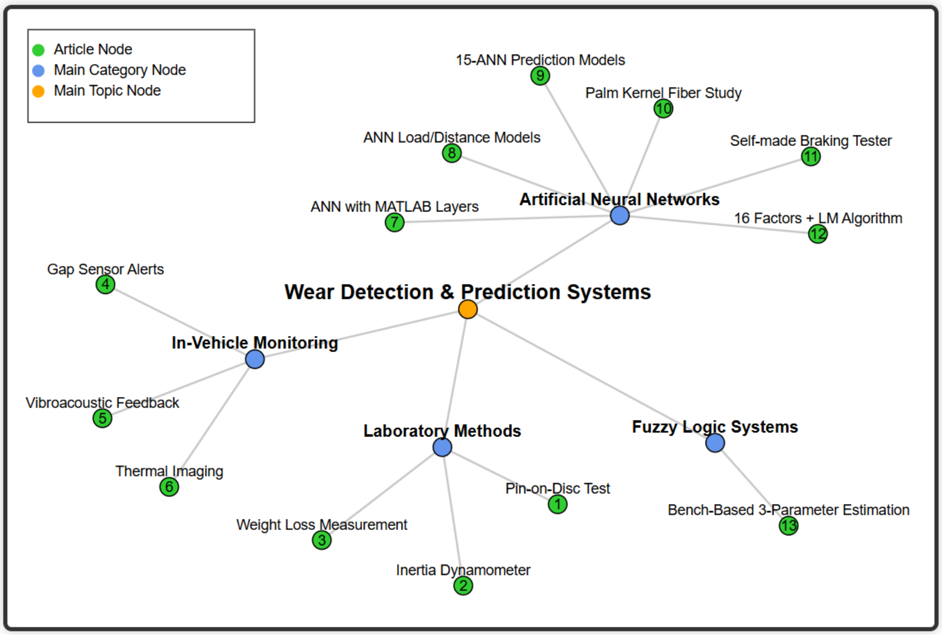

Figure 5. Overview of wear detection and prediction systems for brake pads. Article node: (1)–[6,8,52,57], (2)–[58,61,62], (3)–[62,63], (4)–[1], (5)–[64], (6)–[64], (7)–[30,65,66], (8)–[2,27], (9)–[67], (10)–[68], (11)–[65], (12)–[69], (13)–[63].

6. Conclusions

The wear process of brake pads is a complex function of normal load, material, sliding distance, and a dimensionless parameter: Archard's wear coefficient. While load and sliding distance vary with operating conditions (such as vehicle speed), the hardness of the material primarily depends on the product's initial characteristics. Manufacturers recognize that material properties can change over time—or even during the braking process—necessitating the determination of a variable wear coefficient, i.e., a dimensionless parameter that depends on various factors.

Given the influence of particle emissions on human health, brake pad manufacturers continue to develop new formulations tailored to different disc models and materials, aiming to achieve better chemical affinity between brake components. Chemical affinity influences adhesive wear, frictional interactions, tribofilm formation, and thermal stability. When materials are not well matched, wear rates increase. This aspect is primarily addressed during the prototyping phase, as the effect of chemical affinity on wear can be adjusted by modifying material composition. Wear forecasting systems can be calibrated in laboratory settings by accounting how material properties vary with temperature, load and environmental conditions. A key factor that can affect the wear coefficient is the phenomenon of thermo-elastic instability (TEI), which occurs throughout the brake pad's service life and is influenced by extreme braking conditions–whether intensive or prolonged. The geometry of the brake pads and disc affects temperature distribution and friction coefficient across the radial direction of the braking components. TEI can cause variations in material properties, surface contact, and friction due to combined effects of heat and mechanical stress, thereby altering the wear rate predicted by Archard's law. TEI presents a significant challenge to brake wear prediction systems. Surface characteristics—including texture, roughness, tribofilm formation, and contamination—also influence wear rate. These parameters depend on material properties, environmental conditions, and driving style, making it difficult to precisely quantify their individual contributions to wear. To address these complexities, various systems have been developed to detect or predict brake pad wear. Direct detection methods, such as gap sensors, vibroacoustic sensors, and thermal imaging, are used during prototype testing (e.g., pin-on-disc or inertia dynamometer tests) and in real-world applications, although some of these systems can be costly. When developing a brake pad wear forecasting system, it is essential to distinguish between two categories of influencing variables: predictable and unpredictable. Most design-related parameters can be classified as predictable, while environmental factors (e.g., dust, humidity, and salinity) are inherently unpredictable. Even though automotive manufacturers recommend specific brake pads, users often opt for cheaper alternatives once the vehicle is out of warranty. This practice introduces further unpredictability into the system, particularly in terms of the thermo-elastic instability and chemical compatibility. This study highlights new approaches for predicting brake pad wear, especially under dynamic operating conditions. One direction involves building large databases of vehicle operating data, which can be analyzed using artificial neural networks. Another is the identification, combination, and optimization of suitable algorithms that can be implemented across different vehicle platforms. Ultimately, integrating advanced algorithms with new material technologies holds the potential to reduce production and maintenance costs, minimize failure risks, and decrease overall brake pad emissions throughout the product lifecycle.

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