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Smart brake pad early warning system: enhancing vehicle safety through real-time monitoring

Afif Syam Fauzi[1], Giva Andriana Mutiara[1], Muhammad Rizqy Alfarisi[1], Tedi Gunawan[2], Muhammad Aulia Rifqi Zain[1]
[1]Computer Technology Study Program, Faculty of Applied Science, Telkom University, Bandung, Indonesia
[2]Information System Study Program, Faculty of Applied Science, Telkom University, Bandung, Indonesia

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ABSTRACT

A contributing factor to traffic accidents is brake pad failure, which diminishes braking system performance and extends braking distance. This work develops a prototype utilizing internet of things (IoT) to measure brake pad thickness, hence enhancing driver awareness through real-time monitoring. The system establishes the thickness detection threshold at 75% (3-4 mm) and 50% (5–6 mm) as a cautionary parameter. The thickness parameter employs an American wire gauge (AWG) 18 cable to connect to the ESP32 microcontroller. The web-based IoT monitoring interface employs Laravel. This method enables drivers to get prompt notifications regarding the decrease in brake pad thickness, hence permitting urgent preventative maintenance to mitigate the risk of accidents. The system underwent testing through friction at a rotational speed of 600 to 6,000 rpm. The test findings indicated that the sensor precisely measured the brake pad thickness with a prototype response time of a second. This system is suitable for implementation on old model vehicles that do not have an early warning system. The installation of this technology is anticipated to enhance driver knowledge of the state of the brake pads, hence potentially diminishing the danger of brake system failure caused by unmonitored pad wear.

Corresponding Author:

Giva Andriana Mutiara
Computer Technology Study Program, Faculty of Applied Science, Telkom University
Bandung, Indonesia
Email: givamz@telkomuniversity.ac.id

1. INTRODUCTION

Globally, there are 3,700 deaths due to traffic accidents every day [1]. The factors that cause accidents are due to human error, environmental conditions, vehicle or mechanical errors, and other factors. Although human error is still the biggest factor that causes accidents, mechanical vehicle factors also need to be considered to reduce human error against vehicle maintenance negligence factors. This is because referring to the high number of traffic accidents globally, there are also accidents caused by the failure of vehicle components due to lack of maintenance on some vital components in the vehicle itself. While vehicle-related issues contribute to a smaller percentage, they can have devastating consequences. Mechanical failures are brake failures (2-5%), tire blowouts (2-4%), engine and power loss (1-3%), and light issues (1-2%) [2]. To ensure passenger safety, today's vehicles are equipped with various sensors that are embedded in the vehicle system and can be monitored in real-time. To mitigate the risk of accidents and protect human lives, it is essential to enhance the deceleration mechanisms in vehicles through the integration of early warning system technology [3].

Based on research results, one of the mechanical factor components that is very influential and must be considered for driving safety is brake padding [4]. The primary cause is typically braking failure, which results from inadequate maintenance and deformation of certain components. Brake pads are components of a vehicle that facilitate wheel rotation cessation, enabling effective braking [5]. The friction generated within the brake pads is crucial for the overall performance of the vehicle's braking system [6]. Brake pad damage may arise from multiple factors, typically related to wear and tear, driving behaviors, or mechanical problems. Brake pads experience wear due to friction with the rotors, which is necessary for decelerating the vehicle [7]. This constitutes a standard aspect of their lifespan, generally ranging from 20,000 to 50,000 km of usage, depending upon driving conditions and pad type.

The optimal functioning of the braking system necessitates careful consideration of the durability and quality of the brake padding [8]. Inferior pads exhibit a higher rate of wear compared to premium materials like ceramic or semi-metallic pads. During braking, significant friction produces substantial heat, which enhances the anti-slip effect on the brake lining surface while also leading to gradual wear. The brake lining will progressively thin over time until it reaches the wear threshold [9]. Driver behavior during braking can significantly impact brake pad longevity, as sudden or aggressive braking elevates heat and stress on the pads. The practice of applying brakes with slight pressure while driving can lead to continuous friction and wear. Moreover, the condition of the vehicle while transporting heavy loads or towing can impose additional stress on the braking system.

This research proposes a prototype for an early warning notification system utilizing two American wire gauge (AWG) 18 cables as brake pad condition detection sensors, integrated with an ESP-32 microcontroller to transmit information to a web-based driver dashboard. This system aims to enhance drivers' awareness of mechanical components that necessitate regular maintenance in their vehicles and expanding access to safety technology for more vehicle users. This system indirectly improves driver awareness and modifies braking behavior by discouraging aggressive driving habits and excessive braking. Consequently, it prolongs the lifespan of brake pads and decreases the incidence of traffic accidents attributed to human error and braking system failures. This system enhances vehicle owners' awareness regarding the regular inspection of brake pads, their timely replacement, and the importance of utilizing high-quality brake pads appropriate for specific driving conditions.

The next chapters will describe the literature review and methodology applied in this research. Furthermore, in the third section, the research results are presented along with an in-depth analysis of the evaluation conducted. The last section, namely the fourth chapter, serves as a conclusion that summarizes the entire discussion.

2. METHOD

This section provides a comprehensive overview of the research conducted and the methodology utilized. This study focuses on the prototyping approach, utilizing quantitative methods as the primary reference point. This method acts as a framework for performing the research, encompassing multiple phases that involve an extensive review of existing literature. The literature review outlines the methodology for conducting this research through the development of a prototype that accurately reflects real-world conditions, detailing the general construction of brake linings and their operational mechanisms. The subsequent step involves the design and production of prototypes, informed by insights gained from the literature review. Establishing a scenario testing strategy that accurately reflects the actual environment of the brake padding is essential. The subsequent phase involves executing the test as per the established scenario, followed by an evaluation and discourse on the findings derived from the test results. Ultimately, conclusions will be formulated based on the results acquired.

2.1. Literature review

The braking system of a vehicle is essential for maintaining driving safety. As seen in Figure 1, the brake pad is a crucial element in this system, as it generates the necessary friction to decelerate or halt the vehicle. The friction in the brake lining undergoes wear and tear over time, which, if not monitored, may lead to diminished braking performance and an increased risk of accidents [10]. The driver's insufficient awareness of the brake lining's condition frequently contributes to unforeseen braking failures [11]. Additionally, when the brake lining reaches a minimal thickness, the brake disc (rotor) comes into direct contact with the metal of the lining, potentially leading to damage or deformation of the rotor [12]. Consequently, a method to decrease the incidence of traffic accidents resulting from braking system failure is to conduct maintenance on the vehicle's components [13].

Properly maintained brake pads facilitate uniform pressure distribution, leading to a consistent stop while minimizing vibration and noise. An effective brake system minimizes the strain on the engine, thereby enhancing fuel efficiency and prolonging the lifespan of the vehicle. The thickness of new brake pads is

10-12 mm for the front wheels and 8-10 mm for the rear wheels. As depicted in Figure 2, brake pads that are properly maintained typically follow a scheduled replacement protocol, which dictates that they should be replaced once the thickness reaches the minimum limit of 3-4 mm. Regular assessment of brake lining thickness is advisable every 10,000-20,000 km or in accordance with the manufacturer's specifications [14]. Furthermore, the quality of the material used in the brake lining significantly influences its lifespan.

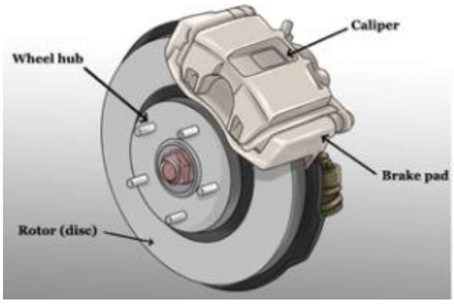

Figure 1. Brake pad structure

Figure 2. Brake pad

The safety of drivers is influenced by both the components of the brake pads and the overall system that facilitates and powers these brake pads. Contemporary automobiles predominantly utilize braking systems that are based on hydraulic principles. Moreover, a range of sensor technologies has been employed to measure brake lining thickness. Research conducted by Wang *et al*. [15] employs a deep learning algorithm featuring a CNN-LSTM model, which has been optimized through the gorilla troops optimization (GTO) algorithm. This method aims to systematically monitor and forecast the thickness of brake lining residue in real-time, enhancing the overall performance of the braking system. The study focuses on enhancing the safety and operational efficiency of the braking system.

Furthermore, the study by Majuma *et al.* [16] introduced a method for monitoring brake lining wear through a sensor-based approach coupled with real-time data analysis. This study employs the on-board diagnostic (OBDII) device as a tool for data collection, focusing on metrics such as brake pad thickness, pressure force applied to the brake pedal, and the temperature produced during the braking process. The data underwent a thorough examination to assess the impact of different road conditions on brake lining wear rates in a more detailed manner. The benefits of this technology are rooted in precise and instantaneous data transmission, along with enhanced maintenance efficiency. This results in a reduction of both time and maintenance expenses. Nonetheless, a notable drawback of this technology is the substantial investment required for the installation and integration of sensors at the outset. Furthermore, it is essential to evaluate the reliability of this technology, as the vehicle's vibrations may influence the wiring and connections of the sensors, potentially leading to malfunctions.

Comprehensive studies have been carried out regarding the evaluation, reliability assessment, and regulation of brake systems [17]. This research emphasizes the necessity of observing the status of essential components, like brake pads, to guarantee optimal performance and prevent possible failures [18]. Some research has been proposed the system that collaborate vehicle owners and service technicians can be better informed about the state of their brake pads, enabling them to make informed decisions about maintenance and replacement schedules [18], [19].

A further investigation carried out by [20] aimed to identify brake lining wear and establish a vehicle health monitoring system utilizing digital twin simulation. This sensor is designed to quantify brake lining wear by analyzing the relationship between applied pressure and rotor speed [20]. This research, which is based on digital twin technology, employs cables as a means to link the sensor with the electronic control unit (ECU). This study employs an anisotropic magneto resistive sensor (AMR) designed to measure wheel speed by identifying variations in the magnetic field experienced by the sensor as the wheel rotates. This approach incorporates the wear rate model, a simulation that evaluates normal pressure on the brake lining and rotor speed to determine brake lining wear, alongside the Archard wear model.

The digital twin simulation carried out by this research has the advantage of high accuracy because the digital twin-based sensor allows precise wear detection. Then this research also involves an ECU that allows fast and efficient data analysis and predictive algorithms [10]. However, the shortcomings of this research are quite complicated because it requires integration between physical models and digital twin-based simulations, as well as relatively expensive implementation costs for standard vehicles.

Despite the extensive development of brake pad condition monitoring technology, its application tends to be confined primarily to premium class vehicles. The absence of access to these safety systems for many ordinary vehicles highlights the necessity for a solution that is both affordable and adaptable. Such a solution should be applicable to a diverse array of vehicles, including older models and those with lower price points.

This research aims to propose a prototype early warning system, characterized by its simplicity and cost-effectiveness, designed to monitor and detect brake lining wear in vehicles. This research involves the fabrication of the brake pad utilizing various forming materials that closely resemble those used in actual brake pads. This study will utilize ESP and VT200 for data transmission, serving as a replacement for OBDII, in contrast to previous studies that employed OBDII as the data interface. The brake pad wear detection system will implement a digital twin concept utilizing an information of twin cable that communicates the condition of the brake pads through two distinct warning levels. The 75% indicate represents the notification status, while the 50% threshold denotes the warning system area, prior to detecting brake pad wear that falls below a thickness of 4 mm. This system is expected to provide safety and comfort solutions to low-cost vehicles, or vehicles that do not have an early warning system notification system for brake pad conditions.

2.2. Brake pad system design

The initial phase in developing a brake pad prototype involves designing a brake pad that incorporates the polymer material research conducted by Irawan *et al*. [21]. The prototype of the brake pad is constructed with multiple layers, as illustrated in Figure 3, which include friction material, an underlayer, adhesive, and a blackplate. The friction material layer comprises a composition that includes reinforcement, abrasive, filler, and binder or resin material.

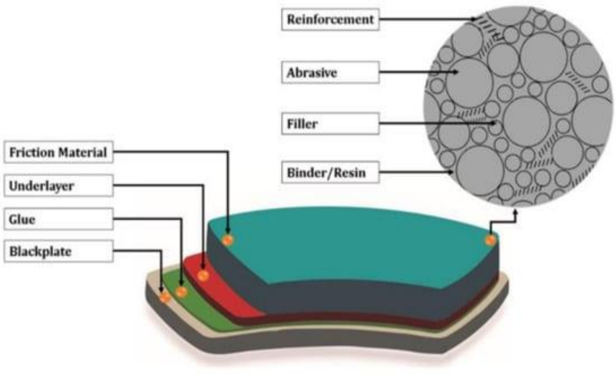

Figure 3. The structure of natural brake pad

Irawan *et al*. [21]. indicate that the adhesive responsible for securing the friction material to the other layers is located on the bottom layer, positioned between the friction material and the back plate. This system operates to mitigate vibrations generated by the interaction of friction material with the disc. In the interim, the back plate of the lining is designed to deliver the essential rigidity to the brake pad, facilitating its continued movement along the caliper guide. Certain industries implement specialized interference shims to reduce the generation of extraneous noise during braking processes. The friction material that directly interacts with the disc during braking is a critical component of the brake pad. The composition of brake pads consists of different materials, each engineered for particular applications.

This study involved the creation of a brake pad prototype utilizing wood powder along with various materials, including glue and multiple plates. The construction of brake pads relies on the consideration of several key factors, including material characteristics, the manufacturing process, environmental influences, and the intended performance outcomes. The characteristics of the material encompass strength, heat resistance, and the friction coefficient [5]. The manufacturing process should systematically guarantee the quality and consistency of the final product. Environmental factors play a crucial role in the selection of environmentally friendly materials, and testing serves to assess the prototype's performance in conditions that closely mimic real-world usage, as illustrated in Figure 4. It illustrates a prototype brake pad layer composed of a blend of sawdust derived from soft organic waste and adhesive glue, subsequently molded to replicate the original brake pads used in vehicles for the purpose of further testing. The materials utilized in the creation of the prototype brake pads from sawdust are composed in a ratio of 5:1:7, specifically for coarse powder, fine powder, and wood glue, respectively. The combination of materials results in a brake pad prototype characterized by a fragile structure, which serves as a means to evaluate the functionality of the brake pad wear system.

Figure 5 illustrates the outcomes of the brake pad manufacturing process. The manufacturing process of this brake pad prototype requires approximately 2 to 3 days for each unit, as it includes a drying phase under sunlight at ambient temperature. The purpose of this drying stage is to solidify the prototype composed of sawdust, ensuring it adheres to the required strength and feasibility standards for testing [22]. The image illustrates a brake pad prototype created from a blend of sawdust, fine powder, and adhesive, resulting in a uniform mixture and becoming a natural fiber composite [23]. The mixture is subsequently shaped to replicate the original brake pads and dried utilizing the surrounding ambient temperature. Additionally, the initial parameters and warning parameters have been incorporated, indicated by a circle on the reverse side of the brake pads. The prototype, once marked, undergoes testing by scraping the material until the two parameters fail. This process evaluates the material's performance and durability under simulated conditions.

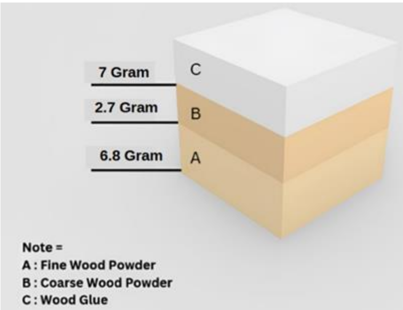

Figure 4. Brake pad layering composition

Figure 5. Brake pad prototype

The subsequent phase involves formulating the construction for simulating the brake pad condition early warning system, as illustrated in Figure 6. At this phase, the brake pad notification system employs cables as a sensor for the warning mechanism. The brake pad design implemented in this study incorporates two early parameter cables and warning parameters utilizing AWG 18 cables. The thickness of the cable significantly influences the optimization of the sensor; therefore, it is essential to select cables with minimal thickness. The implication is that a thicker cable will result in a prolonged erosion process, which may not align with the percentage of the brake pad thickness. The choice of AWG 18 cables, which have a size of 0.404 mm, over AWG 16 is based on the smaller cable size, which allows for insertion into the brake pads that have been perforated at two points [24]. This design will wear down in conjunction with the vehicle's braking usage.

This concept is further substantiated by multiple studies on AWG 18 cables, which exhibit considerable thickness, heat resistance, and the capability to support high bandwidths of up to 1,000 Mbps [13]. The capabilities outlined position it as an ideal option for enabling a gradual transition to next-generation internet of things (IoT) devices, while also significantly reducing costs associated with the infrastructure migration process. For example, AWG 18 cable can be employed in Industrial internet of things (IIoT) systems within smart manufacturing environments, which are crucial for industries operating in harsh conditions, such as the oil and gas sector. This cable facilitates the connection of devices like sensors and actuators, thereby effectively enhancing automation and data integration [13], [24]. Additionally, AWG 18 cables exhibit high resistance to elevated temperatures, extreme pressure, and corrosive environments, making them suitable for industrial applications that require high reliability and durability [24]. Furthermore, the drawback of AWG 18 cable is evident in its low ohmic resistance, which is approximately 23 ohms/km, resulting in minimized power loss [13]. The prototype system, which supports IoT integration, incorporates a light emitting diode (LED) indicator on the vehicle dashboard that activates when the early and warning parameter cables exhibit signs of eroded material, thereby alerting the driver through the dashboard's LED indicator [25].

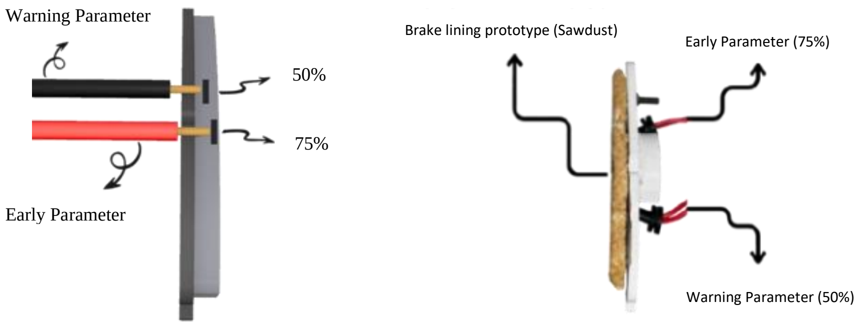

Figure 6. Brake pad layering composition

Figure 7 illustrates a diagram block of a proposed prototype brake pad system developed to facilitate early detection and warning parameters, highlighting the strategic placement of pertinent sensors. This prototype is engineered to facilitate the gradual wear of the brake pads as a result of the disc's rotation at a consistent revolutions per minute (RPM) speed. The brake pads are strategically placed with two non-penetrating holes on the back positioned at the 50% and 75% marks, specifically in regions that are likely to experience wear from the disc.

This design facilitates the precise activation of early warning parameters in response to repeated braking events. When both parameters are disconnected, the resulting data is transmitted and recorded in real-time to the ESP32 microcontroller for subsequent examination. The measurement data is transmitted through the VT200 module to the database for thorough analysis, and the outcomes are displayed in real-time on a website platform accessible to the driver.

The complete measurement system will be provided via a Laravel-based platform, enabling drivers to monitor the condition of the brake pad through a mobile interface. Laravel is an open-source PHP framework utilized for developing web applications based on the model-view-controller (MVC) architecture. Laravel facilitates web application development through its elegant, simple, and efficient syntax. The design of Laravel is not elaborated upon, as the research focuses on the brake pad wear detection system. This monitoring system provides drivers with current information regarding the status of the brake pads and issues timely alerts when the brake pads near a critical wear threshold. This technology offers enhanced safety for drivers and serves as a cost-effective and easily accessible alternative for monitoring driving safety. This invention aims to decrease the incidence of accidents resulting from braking system failures and to broaden the availability of safety technology to a larger number of vehicle users.

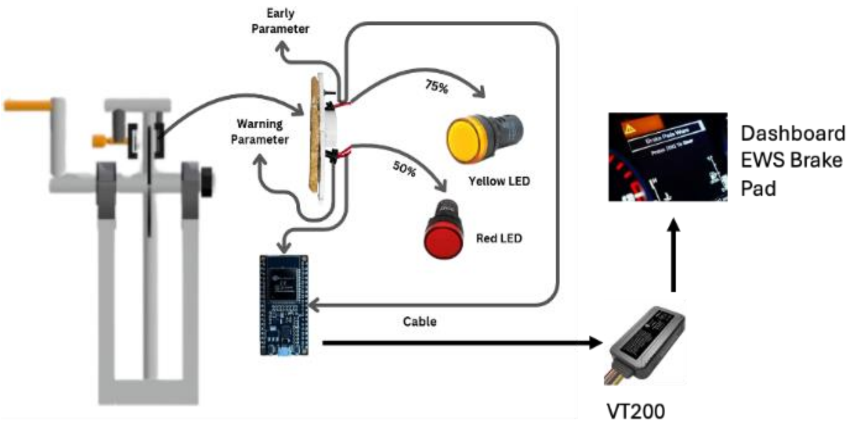

Figure 7. Brake pad system

2.3. Flowchart of the proposed system

Figure 8 presents the system workflow, detailing the comprehensive operational functionality. Figure 8 presents a flowchart that delineates the system workflow associated with this brake pad prototype. Upon activation, the system conducts a comprehensive assessment of all components. The system subsequently evaluates the early warning system (EWS) parameters. If the warning system parameter remains within the range of 75-100%, the dashboard will indicate the LED indicator as OFF, signaling that the brake pad condition is excellent.

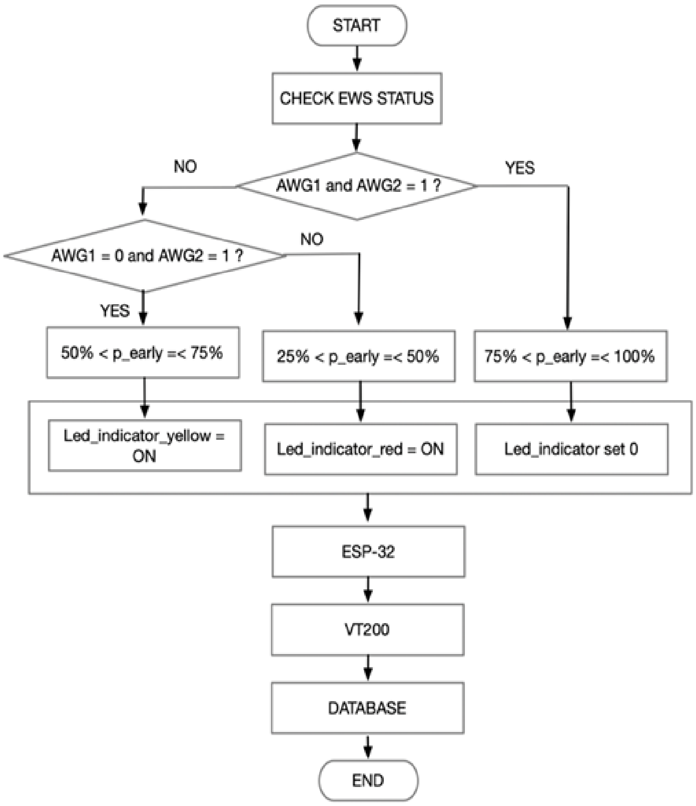

Figure 8. Flowchart of the proposed system

The degradation of the brake pad will persist until it reaches the initial parameter zone, specifically the point where the first AWG 18 cable fails. In the event that the warning system parameter is broken and falls within the early parameter range of 50-75%, the dashboard will indicate yellow to inform the driver about the condition of the brake pads. In the event that destruction persists and encroaches upon the warning parameter range, or if the second AWG 18 cable fails, the system will enter a warning state within the 25-50% parameter area. Consequently, the indicator light will turn on in red, signaling to the driver that the brake pads are in a warning condition. Additionally, the data is transmitted not only to the EWS dashboard but is also recorded in the VT200 and subsequently sent to the EWS monitoring system through the ESP32. The monitoring system can be accessed by the driver or user through a web interface or mobile application.

2.4. Testing scenario

The test scenario for this system involves the utilization of a rotating support, as illustrated in Figure 9. The prototype brake pad is installed on the simulation cross-section plate and subjected to a braking movement that varies from 600-6,000 rpm, as measured by a tachometer. The system sequentially verifies the initial and warning parameters applied via the AWG wire at two specific locations: the initial parameter point located at the 75% thickness position or at 3-4 mm thickness and the first warning parameter point located at the 50% thickness position or at 5-6 mm thickness. This research was conducted as a laboratory test designed to simulate actual conditions, rather than being implemented on vehicles due to the necessity of altering the brake pad structure in the existing vehicle system.

Figure 9. Testing scenario

The brake pads, perforated at 75% and 50%, will be positioned vertically, oriented towards the cable sensor disc known as the early parameter, which is installed in the hole at the top of the brake pads. The hole above will be equipped with an early parameter, which has a depth of 25% of the total initial brake pad thickness (100%). This early parameter will become active when the remaining thickness reaches 75%. The warning parameter sensor is utilized to indicate when the brake pads have reached 50% of their total thickness. The warning parameter will be inserted into the second hole, specifically the bottom hole, when the brake pads are positioned vertically. This hole has a depth of 50% of the initial total thickness of the brake pads. The sensor activates when the brake pads attain a thickness of 50%. Upon the completion of sensor positioning and installation at designated locations, the subsequent phase involves establishing a wired connection between the sensors and the microcontroller board [26]. The microcontroller board is engineered to store and transmit data related to initial parameters and warning parameters to the database. The ESP32 microcontroller enables real-time monitoring through the application of IoT technology [10].

Subsequently, connect the AWG cable tail. The initial end of the AWG cable is linked to the indicator LED, while its other end is connected to the ESP32 microcontroller board [27], [28]. Once all pins are activated, the subsequent step involves activating the microcontroller board by executing the code through the Arduino IDE. Following successful compilation and upload of the code to the board, the serial monitor should be opened to observe the variations in the sensor output. If the brake pad prototype is tested and the early or warning LED indicator activates (TRUE) without any friction occurring, an inspection of the early and warning cables will be conducted. At this stage, the LED indicator should be off, as the early parameter or warning parameter remains connected. Following the inspection, if no issues are identified with the early and warning parameters, the subsequent step will involve a comprehensive examination of the ESP32 microcontroller board, ensuring that the connection between the indicator LED and the microcontroller board is correctly established [29]. Upon the successful installation of all components and systems, the subsequent phase involves testing the erosion of the brake pad prototype [30], [31]. Brake pads installed prematurely, exhibiting warning parameters through two holes measuring 75% and 50% in depth, will undergo erosion testing at a stable RPM. The erosion test is conducted to obtain data from the eroded sensor. The early warning parameter sensors must generate output when the brake pads exceed the specified thickness limit.

3. RESULTS AND DISCUSSION

3.1. Result

Table 1 presents the test results. This scenario serves as an evaluation of the wear characteristics of the brake pad prototype discussed in the preceding chapter. The initial test serves to validate that the location of the early warning point on the brake pad is appropriately situated within the early parameter range (50-75%) and the warning parameter range (25-50%). The confirmation is conducted by analyzing the pad thickness erosion formula over time (Kt) as outlined in (1).

$$Kt = Ko - (r \times t) \quad (1)$$

The erosion formula in this study includes several variables: (t) represents erosion time measured in minutes, (r) denotes the erosion rate in centimeters per minute, (Ko) indicates the initial thickness of the pad in centimeters, (Kt) reflects the thickness of the pad after time (t), and (Qt) signifies the quality of the pad after time (t) minutes. The subsequent formula serves as the primary equation for determining erosion in relation to rotation speed measured in RPM. It incorporates the variable Qt, representing the pad quality after a duration of time t (in minutes), while Qo denotes the initial pad quality, set at 100%. This formula employs a series of calculations, and it also delivers a percentage of pad quality by assessing the pad thickness after a specified duration in relation to the initial thickness. The erosion test was subsequently conducted on one of the brake pads prototypes, focusing on evaluating the erosion in relation to the initial parameters and the warning parameter erosion area data.

$$Qt = \left(\frac{Kt}{Ko}\right) x\ 100\% \quad (2)$$

Table 1. The performance of brake pad prototype

No.	K_0 (cm)	t (minutes)	Kt (cm)	Qt (cm)	Qt (%)
1	0.9	2	0.2	0.7	78
2	0.9	4	0.4	0.5	56
3	0.9	6	0.6	0.3	33
4	0.9	8	0.8	0.1	11

The data presented in Table 1 indicates that as erosion occurs, the thickness decreases, while maintaining a consistent RPM rotation speed results in a regular time interval pattern observed every minute. The positioning of the sensor on the early parameter and warning parameter is suitable and accurately reflects the current state of the brake pad. The data presented in the table indicates that the Qt percentage achieved is 78%, which corresponds to a measurement of 0.2 cm from the brake pad thickness position of 0.9 cm. The AWG 1 cable, serving as a sensor, is strategically positioned at a distance of 0.25-0.3 cm from the thickness of the brake pad prototype to establish the initial parameter location. The AWG 2 cable, serving as the warning parameter sensor, is positioned at 0.45-0.5 cm due to erosion results indicating a 56% impact at the 0.9 cm thickness position. The mapping of the AWG1 and AWG2 sensors positions is illustrated in the graph presented in Figure 10.

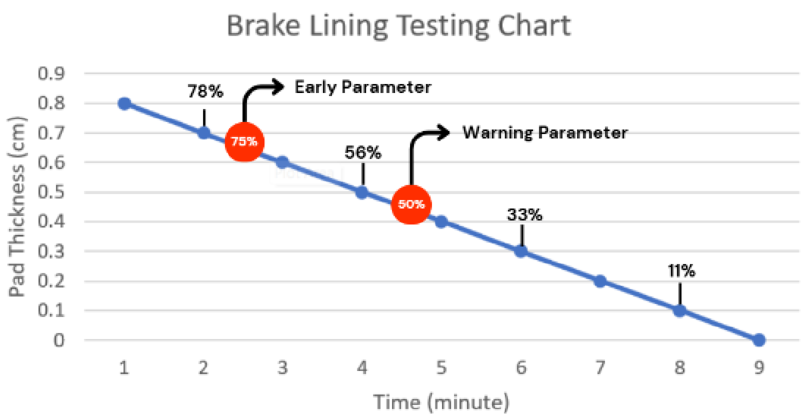

Figure 10. Mapping allocation parameter graph

The subsequent testing involves the operational evaluation of the AWG1 and AWG2 sensors. This test is conducted using a scenario similar to the previous one, where the brake pads will experience erosion at varying rates across a range of 600-6,000 rpm under multiple braking conditions [32], [33]. This test evaluates the effectiveness of communicating pad erosion information to the driver through the dashboard indicator lights and the web display dashboard.

Figure 11 presents the test results. The graph illustrates the variations in brake pad erosion outcomes across three simulated scenarios in the test. The initial scenario involves testing brake pad erosion by assessing the average speed size while RPM increases, with measurements taken at one-minute intervals. The second scenario involves testing brake pad erosion by assessing the average speed size as RPM decreases, with measurements taken every minute. The third scenario involves testing brake pad erosion by assessing the average speed size while RPM fluctuates randomly, with measurements taken every minute.

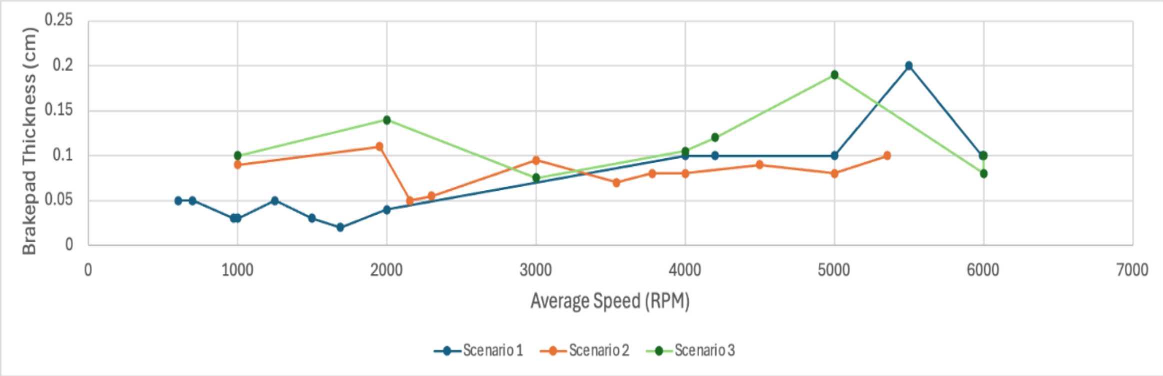

Figure 11. Thickness result testing

The graph indicates that in the initial scenario, where brake pad thickness is evaluated at an escalating speed averaging 2646 RPM, the AWG 1 sensor activates at minute 8 when the brake pad thickness reduces to the initial parameter level of 0.64 cm. AWG 2 then activates at minute 11 when the thickness drops to the warning parameter level of 0.4 cm. Finally, the EWS system halts at the 13-minute mark when the thickness attains 0.1 cm.

In the second scenario, the brake pad thickness is evaluated at a decreasing speed, averaging 3325 RPM. The AWG 1 sensor activates at minute 4, corresponding to a reduction in brake pad thickness to the initial parameter level of 0.63 cm. Meanwhile, AWG 2 activates at minute 7 when the thickness reaches the warning parameter level of 0.4 cm. The EWS system halts at the 11-minute mark when the thickness attains 0.09 cm.

In the third scenario, distinct from the earlier two, the brake pad thickness was evaluated at varying speeds, averaging 3900 RPM. The AWG 1 sensor activated at minute 4 when the brake pad thickness reached the initial parameter level of 0.61 cm, while AWG 2 activated at minute 5 upon the thickness decreasing to the warning parameter level of 0.42 cm. The EWS system halted at the 8-minute mark when the thickness measured 0.01 cm. In each scenario, the parameters of both AWG 1 and AWG 2 sensors are capable of transmitting data through the ESP32 and VT200, which is displayed on a straightforward web dashboard when friction leads to the failure of the brake pad prototype. Figure 12 illustrates the web display that formed by Laravel. The image depicts the state of the brake pad prototype, currently positioned at an early parameter level of 50%.

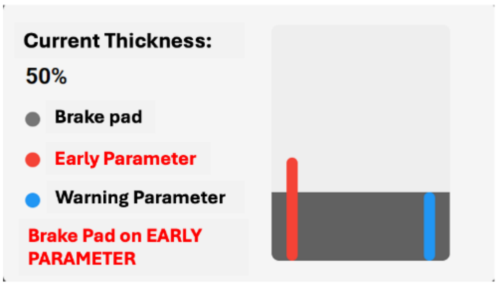

Figure 12. Web interface dashboard

3.2. Discussion

This research aims to develop a brake pad prototype that incorporates a cable-based sensor system, which includes both early parameters and warning parameters. This prototype serves as a novel approach for assessing the quality of brake pads in real-time through the incorporation of cable sensors. This system aims to facilitate the early identification of deteriorating brake pad quality, which in turn is anticipated to enhance both safety and operational efficiency.

The proposed research utilizing two cables as early warning parameters is anticipated to serve as a foundation for subsequent investigations concerning vehicles and brake pad components, emphasizing advancements in technology and enhancements in driver safety. Particularly for low-cost green car (LCGC) vehicles or older model vehicles that necessitate innovation. The main implications of this study include improving driving safety. By detecting brake pad erosion in real-time, this system provides early warning before the brakes reach a critical point. This allows drivers to perform preventive maintenance, reducing the risk of accidents due to worn brakes. Compared to conventional brake monitoring systems based on OBD II or hydraulic pressure sensors, this system has a lower cost and is easy to install on older or non-premium vehicles. This system uses ESP32 to send data to a web-based dashboard, allowing real-time monitoring by both drivers and mechanics remotely. Furthermore, with the notification system, drivers can change their aggressive braking habits and pay more attention to vehicle brake maintenance. Compared to existing early warning systems, the system is only intended for premium class vehicles, so this research is suitable for LCGC class vehicles or public vehicles and old model vehicles.

This study presents certain limitations, as it does not incorporate additional parameters that could enhance accuracy. Specifically, factors such as brake temperature, braking pressure, and friction force have not been considered in the detection model. The system remains independent and lacks the capability for automatic integration with the vehicle system to facilitate emergency braking response when necessary.

Future research can focus on various developments to enhance the accuracy and reliability of the brake pad wear detection system. Improving detection accuracy through the integration of additional sensors is a critical area for development. The incorporation of brake temperature sensors, braking pressure measurements, and accelerometers will enable the system to gather a more extensive dataset for accurately assessing brake pad wear levels. The implementation of magnetic or optical-based sensors enhances the accuracy of detecting variations in brake pad thickness, facilitating more precise and responsive monitoring of vehicle brake conditions. The enhancement of sensor accuracy presents an opportunity for further exploration in the realm of machine learning applications. The creation of machine learning models facilitates the prediction of brake pad wear by analyzing braking patterns alongside historical brake usage data. The system utilizes data from diverse road conditions to deliver a more precise estimation of brake pad lifespan, facilitating enhanced predictive maintenance strategies. To enhance communication with drivers, implementing a more interactive notification system could effectively raise user awareness regarding the status of their vehicle's brakes. Implementing an alert system that provides notifications through a mobile application or short message service (SMS) will guarantee that drivers receive timely information regarding the status of their brake pads directly. The inclusion of the head-up display (HUD) feature offers brake pad wear information in a manner that minimizes driver distraction, thereby enhancing overall driving safety.

To guarantee the system's effectiveness across different conditions, it is essential to conduct testing in real-world scenarios with a broader range of variables. Evaluating the system across diverse terrains, including hilly roads, wet surfaces, and heavy-load vehicles, will yield a more comprehensive understanding of its performance in various driving conditions. Furthermore, assessing the long-term durability of the sensor in relation to extreme environmental conditions, including elevated temperatures and high humidity levels, is essential for confirming the system's reliability in routine applications. A potential avenue for future research involves the integration of electric vehicles with advanced driver assistance systems (ADAS) or VT200. The rising prevalence of electric vehicles necessitates the advancement of systems capable of integrating with regenerative braking technology, thereby enhancing vehicle energy efficiency. Furthermore, integrating these systems with ADAS or VT200 enables vehicles to autonomously modify braking patterns in response to brake pad conditions, thereby enhancing both driving safety and comfort. The advancements in the brake pad early warning system are anticipated to enhance its accuracy, responsiveness, and integration within the contemporary vehicle ecosystem, ultimately leading to improved safety and efficiency in the automotive sector.

4. CONCLUSIONS

The research investigates the automotive sector, focusing on essential vehicle components such as brake pads, and aims to develop an early warning system to enhance driver safety during operation. The system is engineered to deliver real-time data regarding the status of the brake pads to users. The design of this brake pad erosion system prototype closely mimics the braking mechanism found in actual vehicles. The developed method employs a cable as an early warning parameter, effectively delivering notifications through an LED indicator on the vehicle dashboard. This innovation is anticipated to serve as a foundation for advancing research in the area of driving safety. The test results indicate that the proposed system is capable of delivering information to users about the status of the vehicle's brake pads. This research exhibits several weaknesses that present opportunities for improvement and further development in future studies. The implementation of VT200 offers further insights that can be utilized to develop various parameters into a prediction-based system. Future research aimed at enhancing driving safety should prioritize the integration of indicators, supplementary sensors, or additional parameters to refine the accuracy of brake pad monitoring, particularly concerning essential vehicle components. The implementation of a temperature sensor serves to identify thermal variations that may influence brake pad performance. Furthermore, it is essential to pursue the development of cable materials that possess enhanced specifications, extending beyond the use of AWG 18 standard cables, to ensure the overall reliability of the system. The incorporation of additional parameters that can be utilized as predictive models, in conjunction with machine learning or deep learning methodologies, has the potential to enhance the efficacy of the security system.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Afif Syam Fauzi	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Giva Andriana Mutiara		✓			✓	✓	✓	✓	✓	✓	✓	✓		
Muhammad Rizqy Alfarisi	✓		✓	✓			✓			✓	✓	✓	✓	
Tedi Gunawan	✓				✓					✓		✓		
Muhammad Aulia Rifqi Zain						✓		✓		✓	✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, GAM. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

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BIOGRAPHIES OF AUTHORS

Afif Syam Fauzi is a Computer Technology student at Faculty of Applied Sciences, Telkom University. He is involved in several research projects focusing on the internet of things within the Smart Technology and Applied Science Laboratory (STAS-RG). His work primarily revolves around IoT and embedded systems, with a strong emphasis on industrial research solutions. He can be contacted at email: affsyamf@student.telkomuniversity.ac.id.

Giva Andriana Mutiara is an Associate Professor at Telkom University, Department of Applied Science. She completed her Ph.D. in Information and Communication Technology (ICT) from Universiti Teknikal Malaysia Melaka (UTeM) in 2022, and her Master of Engineering in Computer Engineering from Bandung Institute of Technology in 2005. She has participated in several collaborative projects with various industries and received both internal and external grant funding in several research schemes of the Ministry of Research and Technology in recent years. Currently, she is head of Center of Excellence Smart Technology and Applied Science RG and focused her research on Smart Technology and IoT. She holds several intellectual property rights and patents. Her work is reflected in various publications indexed in reputable databases. She can be contacted at email: givamz@telkomuniversity.ac.id.

Muhammad Rizqy Alfarisi is a Lecturer in the Computer Engineering Department at Telkom University. He earned both his bachelor's and master's degrees in computer engineering from the Bandung Institute of Technology, Indonesia. Currently, he serves as a researcher at the Center of Excellence for Smart Technology and Applied Science. He has actively participated in numerous collaborative research projects with various industries, securing both internal and external grant funding through diverse schemes. He holds several intellectual property rights and patents. His research contributions are evidenced by numerous publications indexed in reputable databases. He can be contacted at email: mrizkyalfarisi@telkomuniversity.ac.id.

Tedi Gunawan is a Lecturer in the Department of Information Systems at Telkom University. He obtained his bachelor's degree in engineering at Jenderal Achmad Yani University, Bandung and master's degree in information systems at STMIK LIKMI, Indonesia. Currently, he is a researcher at the Center for Excellence in Applied Science and Technology. He has actively participated in various collaborative research projects with various industries, obtaining internal and external grants through various schemes. He can be contacted at email: tedigunawan@telkomuniversity.ac.id.

Muhammad Aulia Rifqi Zain currently is a student of Telkom University majoring multimedia engineering technology. He invoved in several research that focus on internet of things such in Smart Technology and Applied Science Laboratory. He is focused on embedded system and industrial research solution. He can be contacted at email: muhammadauliarifqi@student.telkomuniversity.ac.id.