IoT-Based Early Warning System for Brake Fading Risk Based on the Increase Rate in Temperature and Vehicle Speed

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Abstract - Brake fading is a critical safety problem caused by excessive heat accumulation on disc brake components during repeated or prolonged braking, leading to a significant reduction in braking force. This research develops an ESP32-based early warning system that monitors disc brake temperature and vehicle speed in real time to detect brake fading risk before a critical condition occurs. The system uses a K-type thermocouple with a MAX6675 module for temperature acquisition and a BN-220 GPS module for speed acquisition, with OLED, LED, and buzzer as local outputs, plus a Telegram bot and web dashboard for remote monitoring. The R&D method was applied, covering design, hardware/firmware implementation, sensor calibration, and road testing on a real vehicle. Calibration results show a thermocouple accuracy of 97.10% (error 2.90%) and a GPS speed-reading accuracy with an average error of 2.75% against the vehicle speedometer. Road tests across six speed variations (20–120 km/h) confirm that brake disc temperature rises proportionally with speed, with the warning indicator correctly switching from green to yellow at the caution threshold and to red with an active buzzer above the critical threshold. The system is expected to serve as a preventive safety tool supporting motor vehicle inspection and testing.

Keywords – brake fading, early warning system, disc brake, ESP32, Internet of Things

1. INTRODUCTION

The State Police Traffic Corps of the Republic of Indonesia (Korlantas Polri) records that the number of traffic accidents in Indonesia reached 116,411 cases in 2019, decreased to 100,028 cases in 2020, but increased again to 103,645 cases in 2021, indicating that road safety remains a serious issue [1]. The majority of these incidents are caused by technical vehicle factors, and one of the main causes frequently identified is the failure of the braking system (brake failure), which remains a serious problem in road transportation safety aspects [2], [3].

The braking system of a vehicle is a vital safety component designed to facilitate safe movement by slowing down or stopping the vehicle's speed in a controlled manner [4]. Among the various types of available technology, disc brakes have become the primary standard in modern vehicles due to their operational efficiency in reducing speed compared to other conventional systems [5]. This braking mechanism generally relies on the hydraulic principle, wherein oil pressure drives a piston to clamp the brake pad against the brake disc that rotates together with the wheel [6]. The intense physical contact between these components creates the resistance force required to maintain vehicle stability and control under various operational conditions.

Physically, the braking process is a direct application of the Law of Conservation of Energy, wherein approximately 80% of the vehicle's kinetic energy is converted into heat energy through friction between the brake pad and the brake disc [7]. The sustained friction interaction

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triggers a significant increase in brake temperature, which is directly proportional to the initial speed, vehicle mass, and the duration of brake pedal depression [2]. If the accumulated heat is not dissipated effectively, excessive temperature can trigger the phenomenon of brake fading, a condition in which the braking force decreases drastically due to weakening of the coefficient of friction, as well as the risk of vapor lock resulting from the boiling of brake fluid, which can cause total braking failure.

The identification of the primary problem in disc braking systems at high speeds is the emergence of the brake fading phenomenon, which directly threatens driving safety. When a vehicle travels at high speed and applies braking, constant friction between the brake pad and the disc will convert kinetic energy into thermal energy in very large quantities [8],[9],[10]. This extreme heat accumulation often reaches the thermal limit of the braking material, thereby triggering structural degradation of the organic components of the brake pad, which results in a significant decrease in the coefficient of friction, causing the brake to lose its gripping force even though the pedal is depressed very hard [11], [12]. Based on the aforementioned explanation, brake fading is a critical problem that causes braking failure; therefore, a more in-depth analysis is required regarding the influence of increased vehicle speed on the thermal stability of the system.

This phenomenon is not merely theoretical but has also been proven to occur in the field. Based on data from the National Committee for Transportation Safety (KNKT), as of March 2025, a total of 222,602 cases of traffic accidents involving freight transport vehicles have been recorded, the majority of which were triggered by braking system failure and unmonitored overload conditions. One concrete case is the chain-reaction accident on the Cipularang Toll Road Km 112 toward Bandung–Jakarta on 2 December 2025, which involved nine vehicles caused by a box truck that was unable to control the vehicle's speed due to a pre-existing braking system problem [13]. Another case is a tour bus accident in Batu City, Malang on 8 January 2025, which according to KNKT occurred due to brake overheat during excessive braking on a downhill road, causing the brake pad to undergo sublimation and form a gas layer that impedes braking force, despite the brake system showing no mechanical damage [14]. Both cases demonstrate that brake temperature information alone is insufficient if not accompanied by an early warning system capable of detecting potential failure from the onset.

In the context of motor vehicle testing, braking system testing generally still focuses on measuring braking force and brake balance, while the aspect of brake thermal condition, particularly the potential for failure due to excessive heat, has not yet become a directly observed parameter. As a result, vehicles that are statically declared to have passed inspection may experience a decrease in braking performance when operating under hot conditions in the field. Based on this problem, there is a need for a system design that not only functions as a brake temperature monitoring tool but is capable of providing early warning based on analysis of temperature increase and vehicle speed as an early indicator of brake fading occurrence. Previous research has generally still focused on the function of real-time brake temperature monitoring without predictive analysis and has not yet linked the developed system with the requirements of motor vehicle testing [9], [11], [12]. Based on this research gap, this research proposes the design and development of an early warning system for brake fading risk on disc brakes based on ESP32 that analyzes the rate of brake temperature increase along with vehicle speed data from a GPS sensor, so that it is expected to serve as a preventive solution that provides a tangible contribution in supporting motor vehicle testing.

2. RESEARCH METHOD

The research method employed in the design and development of an Internet of Things (IoT)-based early warning system for brake fading risk is the Research and Development (R&D) method. The R&D method was selected because this research aims to develop a new product in

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the form of an early warning system, the success of which must be demonstrated through a series of tests under actual operational conditions, not merely through laboratory testing.

The research was conducted at the East Brebes Toll Gate, Brebes Regency, Central Java, with the implementation period ranging from January to June 2026.

The first stage is literature review, which focuses on understanding the technical characteristics of the components used, including the working principle of type K thermocouple and MAX6675 module, ESP32 microcontroller architecture, SPI and I2C communication protocols, as well as the implementation of ESP32-based IoT systems for data transmission to Telegram and web dashboard. The second stage is problem formulation, which specifically establishes the system requirements to measure disc brake temperature in real-time, calculate the rate of temperature increase as an indicator of brake fading risk, and deliver early warning to the driver through local indicators as well as remote notifications.

The The third stage is equipment requirement analysis, which identifies all hardware and software components required based on the functional specifications of the system. The fourth stage is equipment design and assembly, which includes the creation of a system block diagram as shown in Figure 1, a system working diagram as shown in Figure 2.

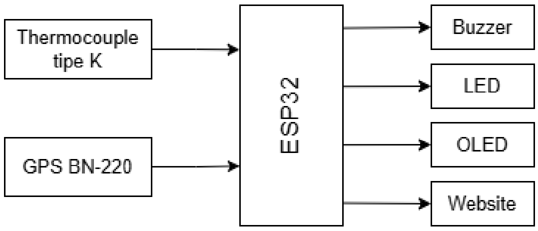

Figure 1. Diagram Block

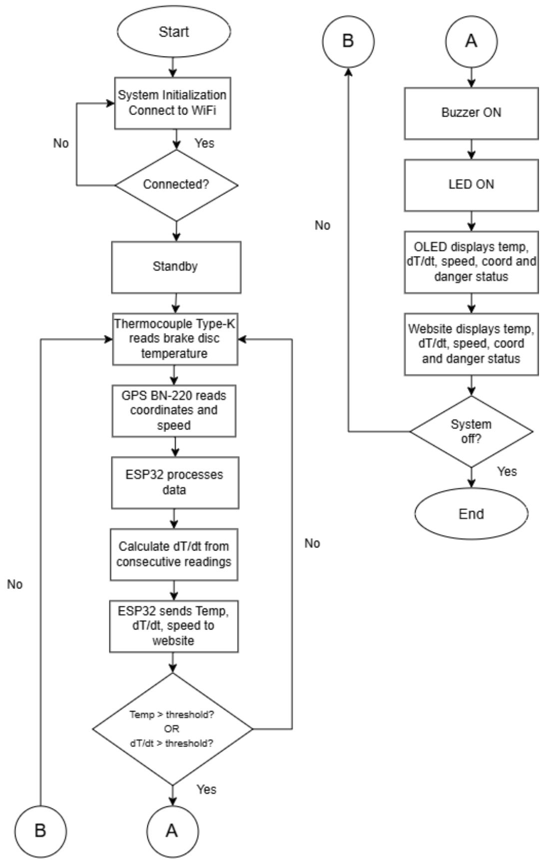

Figure 1 Working diagram of the system

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Figure 2 illustrates the working flowchart of the system. When the device is powered on, it performs system initialization and attempts to connect to WiFi; if the connection fails, the system retries the initialization process until a connection is established, after which it enters standby mode. The system then continuously executes a monitoring loop in which the K-type thermocouple reads the disc brake temperature, the BN-220 GPS module reads the vehicle's coordinates and speed, and the ESP32 processes this data. At each cycle, in addition to recording the current absolute temperature, the ESP32 computes the rate of temperature increase (dT/dt) from two consecutive temperature readings, following Equation (3), and sends both values to the web dashboard. The system then evaluates a dual-criterion condition: a warning is triggered if either the absolute temperature exceeds the predefined threshold (80°C for Alert, 120°C for Danger) or the computed dT/dt exceeds the corresponding rate threshold (1.0°C/minute for Alert, 2.0°C/minute for Danger), whichever is satisfied first. If neither condition is met, the system loops back to continue the monitoring cycle. If either condition is met, the system activates the buzzer and LED, and displays the temperature, rate of increase, speed, coordinates, and danger status on both the OLED display and the web dashboard. The system then checks whether it has been turned off; if not, it returns to the monitoring loop while maintaining the active warning, and if so, the process ends.

The fifth stage is equipment and website programming, which includes the development of microcontroller firmware using Arduino IDE and the development of a web-based monitoring dashboard. The circuit schematic that serves as the reference for programming is shown in Figure 3.

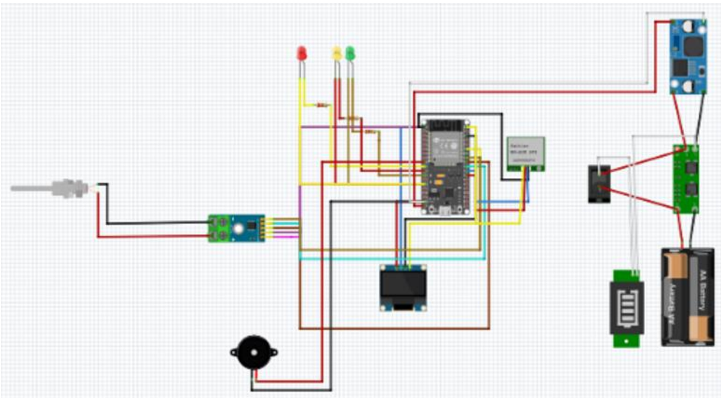

Figure 2. Circuit schematic in the Fritzing application

The main hardware components used in this research are presented in Table 1.

Table 1. Hardware Components Used

No	Component	Function
1	ESP32	Serves as the main processor that processes data from all sensors.
2	Type K Thermocouple	Acts as the temperature sensor detector on the disc brake.
3	MAX6675 Module	Converts the thermocouple signal into digital data readable by the microcontroller.
4	BN-220 GPS	Determines the vehicle's position, speed, and time in real-time.
5	OLED Display	Displays brake temperature data and system status.
6	Buzzer	Provides warning sound when overheat condition occurs.

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7	LED (green/yellow/red)	Visual indicator of brake temperature condition (normal/alert/danger).
8	Step-down Module, 2S BMS, Lithium Battery	Provides and regulates power supply for the entire circuit.

The sixth stage is equipment testing and calibration. If the test results do not meet the established criteria, the process is returned to the programming stage for improvements. Thermocouple sensor calibration was performed by attaching the sensor to the surface of heated iron and then comparing the results with a thermogun, while BN-220 GPS calibration was performed by comparing the GPS speed value against the vehicle speedometer at five speed variations. If the test results meet the criteria, the research proceeds to the results discussion stage.

The seventh stage is equipment installation on the test vehicle, namely the Toyota Innova. The thermocouple sensor was installed on the rear disc brake using a metal bracket fastened to the brake caliper bolt, with the sensor tip directed toward the disc surface without making direct contact with rotating components, as shown in Figure 4.

Figure 3. Thermocouple Sensor Installation on the Disc Brake

The eighth stage is equipment testing through road testing, which involved driving the vehicle under real-world traffic conditions along a combination of urban city roads and toll roads at six target speed variations (20, 40, 60, 80, 100, and 120 km/h), with data recording intervals of every 5 minutes over 35 minutes for each speed variation, to determine the relationship between vehicle speed, braking behavior, and the rate of temperature increase of the disc brake. Rather than following a fixed, pre-scheduled braking interval, braking events occurred naturally in response to real traffic conditions encountered on each road type, such as intersections, traffic signals, other vehicles, and toll gates on urban roads, and speed adjustments and occasional deceleration on toll roads. Each braking application was performed firmly and deliberately (moderate-to-firm pedal pressure, comparable to controlled normal braking rather than gentle coasting or emergency braking), but the exact frequency and duration of individual braking events were not instrumented or logged, since the test was designed to reflect ecologically valid, real-world driving behavior rather than a laboratory-controlled braking protocol.

The classification of brake fading risk levels in the system was established based on three temperature thresholds, namely Normal condition (green LED) at temperature below 80°C, Alert condition (yellow LED) in the range of 80–120°C, and Danger condition (red LED accompanied by buzzer activation) at temperature above 120°C. These thresholds were deliberately set well below the friction-fade onset temperatures reported in the automotive engineering literature, where organic brake pad compounds begin to exhibit a measurable decline in friction coefficient only above approximately 175–200°C and undergo severe degradation by 300–350°C [15]; standardized dynamometer fade-test procedures such as SAE J212 likewise evaluate friction

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performance across a comparable high-temperature range well beyond the thresholds adopted here[16]. Field data on commercial vehicles further show that repeated downhill braking can raise brake system temperatures to around 290°C before mitigation, underscoring that the 80–120°C range represents an early, preventive stage well ahead of critical thermal conditions observed in practice [17]. Field measurements on disc brakes and alternative friction materials further confirm that sustained braking under realistic driving conditions is required before temperatures approach levels associated with measurable wear and emission changes[18]. On-road measurements of passenger car brake components further show that pad and disc temperatures typically remain below 50°C under normal driving, rising to approximately 80°C during hard braking and prolonged descents, and to approximately 120°C after repeated braking events from highway speed[19]. Accordingly, the 80°C and 120°C thresholds used in this study were selected not as the temperatures at which fading actually begins, but as conservative, early-warning boundaries that flag thermally demanding braking conditions well in advance of the critical temperatures associated with actual fade onset, consistent with the preventive design objective of this system.

3. RESULTS AND DISCUSSION

3.1 Results of Hardware and Software Design

The results of hardware design in the form of a brake fading early warning device that has been completed and assembled in a box enclosure are shown in Figure 5. The front panel of the device contains an OLED display as a real-time temperature data indicator, three indicator LEDs in green (normal), yellow (alert), and red (danger), one buzzer unit as a sound alarm, as well as a battery level indicator. The type K thermocouple sensor cable connected to the vehicle's disc brake exits through the upper part of the enclosure.

Figure 4. Results of Brake Fading Early Warning Device Design

The results of software design were realized in the form of a web-based monitoring dashboard developed using the MQTT protocol through a Node-RED broker, as shown in Figure 6. The dashboard presents gauge indicators for vehicle speed and brake temperature in real-time, GPS position information (latitude, longitude, altitude, number of satellites), safety status (Safe/Alert/Danger), as well as historical data logs that can be filtered based on time range or status category, with a data export feature to PDF format.

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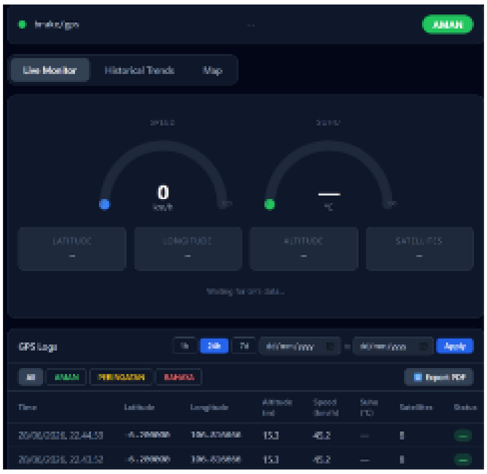

Figure 5. Web-Based Monitoring Dashboard Interface

3.2 *Thermocouple Sensor Calibration*

Thermocouple sensor calibration was performed through ten test trials by comparing the sensor reading results against the thermogun measurement device. The calibration results are presented in Table 2.

The percentage error and accuracy of the thermocouple and GPS sensor readings against the reference instruments were calculated using Equations (1) and (2):

$$Error\ (\%) = \frac{Xsensor - Xreference}{Xreference} \times 100\% \qquad (1)$$

$$Accuracy\ (\%) = 100\% - Error(\%) \qquad (2)$$

where Xsensor is the value measured by the sensor (thermocouple or GPS), and Xreference is the reference value obtained from the thermogun or the vehicle speedometer.

Table 2. Results of Thermocouple Sensor Calibration Compared to Thermogun

Trial	Sensor (°C)	Thermogun (°C)	Accuracy(%)	Error(%)
1	37.4	35.5	94.92%	5.08%
2	59.25	57.2	96.54%	3.46%
3	61.5	60.0	97.56%	2.44%
4	66	64.4	97.58%	2.42%
5	63.25	61.5	97.23%	2.77%
6	60.25	58.7	97.43%	2.57%
7	59.5	57.2	96.13%	3.87%
8	61.25	59.6	97.31%	2.69%
9	59.25	57.9	97.72%	2.28%
10	58.25	57.4	98.54%	1.46%
Average			97.10%	2.90%

Based on Table 2, the relationship between the thermocouple sensor reading results and the thermogun at each trial is shown in Figure 7.

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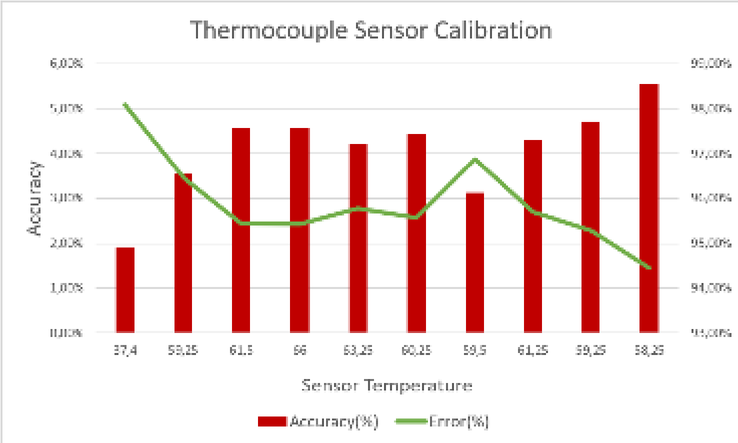

Figure 6. Graph of Thermocouple Sensor Calibration Compared to Thermogun

The calibration results demonstrate that the thermocouple sensor has an average accuracy rate of 97.10% with an average error of 2.90%. The pattern in Figure 6 shows that the sensor reading curve and thermogun curve move consistently and overlap at almost all test points, indicating that the thermocouple sensor can operate optimally and accurately for disc brake temperature measurement applications, although there is still a minor discrepancy that falls within the acceptable tolerance limit for non-critical temperature monitoring applications such as this system.

3.3 GPS BN-220 Sensor Calibration

Calibration of the BN-220 GPS sensor was performed to evaluate the accuracy level of speed reading before the sensor was used as a measurement instrument in brake fading testing. The calibration process was conducted by comparing the speed value read by the BN-220 GPS against the vehicle speedometer reading at five speed variations. The calibration results are presented in Table 3.

Table 3. Results of GPS BN-220 Sensor Calibration Compared to Vehicle Speedometer

Trial	GPS (Km/h)	Speedometer (Km/h)	Δ Speed (Km/h)	Error (%)
1	17.7	17.1	0.6	3.39
2	34.8	33.5	1.3	3.74
3	49.5	48.5	1.0	2.02
4	52.7	51.5	1.2	2.28
5	68.8	67.2	1.6	2.33
Average	44.7	43.6	1.14	2.75

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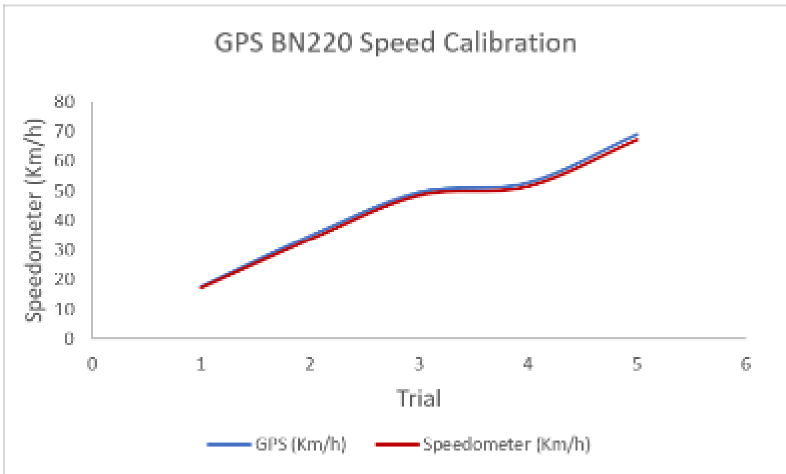

Figure 7. Graph of GPS BN-220 Sensor Calibration Compared to Vehicle Speedometer

Based on Table 3 and Figure 8, the speed reading difference ($\Delta speed$) between the BN-220 GPS and the speedometer ranges from 0.6–1.6 km/h with an average value of 1.14 km/h, while the error percentage is in the range of 2.02–3.74% with an average of 2.75%. The nearly overlapping graph pattern in Figure 7 indicates that the speed change detected by the GPS follows the vehicle's speed change well, therefore the speed data from the BN-220 GPS sensor can be considered representative as a supporting parameter for brake fading testing in the subsequent stage.

3.4 System Output Test Results

System output testing was performed to ensure that the OLED display, speaker (buzzer), and LED can respond to temperature changes according to the design. The test results are presented in Table 4.

Table 4. Results of System Output Testing Under Temperature Variations

No	Detected Temperature (°C)	Display OLED	Speaker	LED	Remarks
1	37.5 °C/40.25 °C	Functioning	On	Green	Good
2	59.25 °C /62.50 °C	Functioning	On	Green	Good
3	81.20 °C/ 87.75 °C	Functioning	On	Yellow	Good
4	95.75 °C/ 100.50	Functioning	On	Yellow	Good
5	123.50 °C/126.25	Functioning	On	Red	Good

Based on Table 5, all system outputs function according to the designed operating principles. The OLED display consistently displays the temperature value from the sensor reading, the LED changes color according to the established temperature threshold (green for normal condition, yellow for alert, and red for danger), and the speaker activates as an alarm when the temperature enters the danger category. These results demonstrate that the integration between the sensor, processing logic on the ESP32, and output components operates as intended.

3.5 Road Test Results

System testing of disc brake temperature monitoring was conducted at six vehicle speed variations, namely 20, 40, 60, 80, 100, and 120 km/h, with observation intervals of every 5 minutes over 35 minutes for each speed variation. The test results are briefly presented in Table 5, while the temperature increase curve across all speed variations is shown in Figure 9.

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The rate of disc brake temperature increase during each observation interval was calculated using Equation (3):

$$\Delta T/\Delta t = (Tfinal - Tinitial) / (tfinal - tinitial) \quad (3)$$

where $\Delta T/\Delta t$ is the rate of temperature increase (°C/minute), Tfinal and Tinitial are the disc brake temperatures (°C) at the end and the start of the observation interval, and tfinal and tinitial are the corresponding observation times (minute).

Table 5. Summary of Road Test Results Under Vehicle Speed Variations

Speed	Temperature at Minute 5 (°C)	Temperature at Minute 35 (°C)	Increase (°C)	Final Status
20 km/h	30.3	41.1	10.8	Normal
40 km/h	35.3	54.5	19.2	Normal
60 km/h	43.9	76.9	33.0	Normal
80 km/h	52.4	101.6	49.2	Alert
100 km/h	63.1	132.1	69.0	Danger
120 km/h	74.1	168.9	94.8	Danger

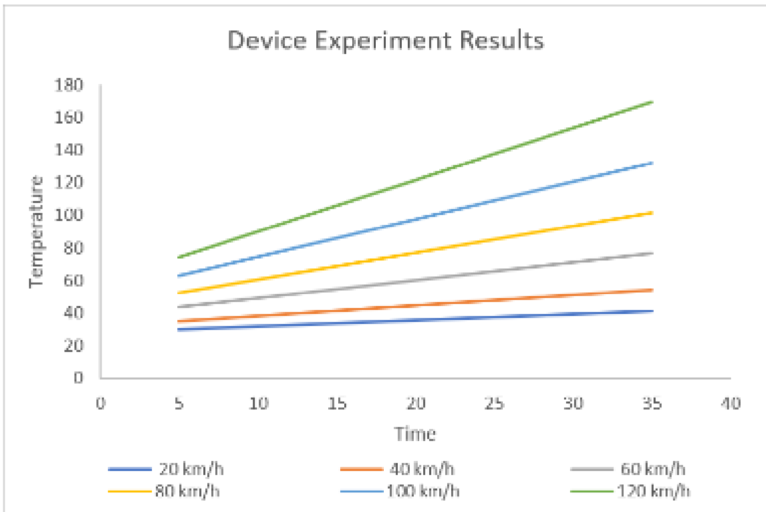

Figure 8. Graph of Disc Brake Temperature Increase as a Function of Time at Different Vehicle Speeds

Based on Table 5 and Figure 9, brake temperature increased across all speed variations. At a speed of 20 km/h, the temperature increased from 30.3°C to 41.1°C, while at a speed of 120 km/h the temperature rose sharply from 74.1°C to 168.9°C within the same observation timeframe. These results demonstrate that the higher the vehicle speed, the greater and faster the temperature increase generated during the braking process, in line with the increase in kinetic energy converted into heat energy through friction between the brake pad and disc.

The early warning system developed was able to provide responses according to the established temperature threshold. In testing at speeds of 20–60 km/h, the temperature remained in the normal condition range, so the LED indicator remained green and the buzzer did not activate. At speeds of 80–100 km/h, the temperature entered the range of 85–120°C, causing the indicator to change to yellow as a sign of alert condition. Subsequently, at speeds of 100–120 km/h, temperatures exceeding 120°C caused the indicator to change to red accompanied by buzzer

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activation as an early warning. Temperature condition notifications were also successfully received consistently through the Telegram application across all testing scenarios.

The increasingly steep slope of the curve in Figure 9 at higher speeds indicates that the rate of brake temperature increase ($\Delta T/\Delta t$), rather than the absolute temperature value alone, is significantly affected by the vehicle's initial speed. This finding reinforces the theoretical basis employed in this research, namely that the rate of temperature increase is a more sensitive and predictive indicator of brake fading risk compared to absolute temperature alone, because it is able to detect risky conditions even before the temperature reaches a critical value. Therefore, the integration of temperature data and vehicle speed in the developed system has proven effective in providing early information regarding the potential occurrence of brake fading under high thermal load braking conditions, and thus has the potential to be applied as an auxiliary tool in the motor vehicle testing process.

3.6 Study Limitations

It should be noted that the temperature reported in this study corresponds to the reading of a K-type thermocouple positioned near the brake disc surface using a metal bracket mounted on the caliper bolt, rather than a sensor embedded directly within the friction interface between the pad and the disc. As a result, the measured value represents the air/near-surface temperature in the vicinity of the disc rather than the actual instantaneous temperature at the pad-disc friction contact, which is known to be substantially higher and more spatially non-uniform due to localized frictional heating during active braking, with prior disc/pad interface studies reporting substantially higher and more transient temperatures at the true friction contact than at nearby measurement points [20]. This measurement approach was adopted for practicality and non-invasiveness in a real-vehicle, real-road setting, and is consistent with common practice in low-cost brake monitoring systems; however, it implies that the absolute temperature values reported in this study should be interpreted as a proxy indicator of thermal loading trends rather than as a precise measurement of the true friction surface temperature. Future work may address this limitation through embedded or non-contact (e.g., infrared) temperature sensing closer to the friction interface.

4. CONCLUSION

This research has successfully designed and developed an ESP32-based early warning system for brake fading risk on disc brakes that integrates a type K thermocouple sensor, MAX6675 module, and BN-220 GPS module to monitor brake temperature and vehicle speed in real-time. The system employs a dual-criterion warning algorithm that evaluates both the absolute brake temperature and the rate of temperature increase (dT/dt) at every monitoring cycle, triggering Alert and Danger warnings whenever either criterion is met. Calibration results demonstrate that the thermocouple sensor has an average accuracy of 97.10% (error of 2.90%), while the BN-220 GPS sensor has speed reading accuracy with an average error of 2.75% against the vehicle speedometer, indicating that both sensors are suitable for use as measurement instruments in this system.

Road test results across six speed variations (20–120 km/h) demonstrate that the rate of disc brake temperature increase is directly proportional to vehicle speed, ranging from 0.36°C/minute at 20 km/h to 3.16°C/minute at 120 km/h, with the highest temperature increase occurring at 120 km/h, namely 94.8°C over the 35-minute observation period. When validated against this dataset, the proposed dT/dt thresholds (1.0°C/minute for Alert and 2.0°C/minute for Danger) were found to trigger a warning at 60 km/h earlier than the absolute-temperature criterion alone, since the measured rate (1.10°C/minute) exceeded the Alert threshold even though the final temperature (76.9°C) remained just below the 80°C absolute threshold, demonstrating the added predictive value of incorporating dT/dt into the warning algorithm. Therefore, this system can serve as a relevant preventive auxiliary tool to support driving safety and improve the quality of

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motor vehicle testing processes, particularly in the aspect of monitoring the thermal condition of the braking system, which has not yet been a directly observed parameter.

Further development is still required, especially in validating the proposed dT/dt thresholds through controlled, instrumented braking protocols with logged brake pedal force, frequency, and duration; refining the threshold determination algorithm adaptively based on vehicle characteristics and road conditions; incorporating friction-surface temperature estimation to complement the current near-surface thermocouple measurement; expanding the variety of testing conditions such as downhill roads and fully loaded vehicles; and validating the system across various types and categories of vehicles, to ensure this system becomes increasingly relevant and reliable for widespread field application.

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