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The Design and Empirical Analysis of Smart Tire Monitoring System using Cloud and Docker Container Technology

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Abstract— Modern vehicles rely on Tire Pressure Monitoring Systems (TPMS) to improve safety and enhance the driving experience by monitoring tire pressure and temperature. Traditionally, TPMS systems rely on specialized hardware to collect and transmit data to the vehicle's onboard computer, making this information accessible solely to the driver. This study proposes an enhanced TPMS that leverages Cloud and Docker Container technologies. The Message Queuing Telemetry Transport (MQTT) protocol enables efficient communication between a cloud server and a central controller. At the same time, Docker containers support streamlined application integration and deployment. Findings indicate optimal standard deviations for tire pressure at 1.8 during the day and 1.2 at night, with temperature deviations at 1.54 during the day and 1.23 at night, showing minimal fluctuation. This setup supports real-time, remote monitoring of tire data, accessible through a smartphone interface. This system offers significant practical benefits, including improved driver awareness and preventive maintenance capabilities. However, potential challenges such as data security, system reliability, and integration with existing vehicle infrastructure warrant further investigation to ensure widespread adoption and effectiveness.

Keywords— Smart Tire; Monitoring System; Cloud Technology; Docker Container Technology; Internet.

I. INTRODUCTION

The automotive industry has undergone rapid development in recent years, particularly in terms of vehicle performance and safety. One crucial aspect of vehicle safety is tire pressure monitoring, as low tire pressure can reduce fuel efficiency, disrupt driving comfort, and increase the risk of accidents. Therefore, the Tire Pressure Monitoring System (TPMS) has become an essential part of modern vehicles, significantly contributing to improved road safety [1]-[3].

Traditional TPMS designs have focused on providing real-time tire pressure data to drivers through specialized hardware integrated into vehicles. While these systems improve safety, they face limitations such as restricted data access, high hardware costs, and limited scalability. Recent studies, such as those in [4]-[6], have extensively explored TPMS applications in four-wheeled vehicles, offering novel approaches to detecting tire pressure loss [7]. In [8], research was conducted on designing and implementing an IoT-based TPMS for hatchbacks and Multi-Purpose Vehicles. Furthermore, in [9], we also researched the application of Software Defined Radio (SDR) in TPMS. In [10], we proposed a communication system between TPMS and servers using a combination of Orthogonal Frequency Division Multiplexing (OFDM) and Convolutional Code. Overall, these studies highlight the crucial role of TPMS in optimizing tire performance and safety, providing information on tire conditions, and enabling preventive actions to mitigate potential road hazards.

Cloud computing presents a promising solution by leveraging the Internet to provide flexible, scalable, and efficient resource management [11]. Integrating cloud technology into TPMS allows tire pressure and temperature data to be processed, stored, and accessed in real-time through remote servers. This capability enables vehicle operators and fleet managers to monitor tire conditions via mobile applications, improving safety, operational efficiency, and fleet management [12][13]. However, implementing cloud-based TPMS introduces challenges related to security, data management, and seamless integration with existing systems.

Docker containerization offers a complementary solution by packaging applications and their dependencies into portable, isolated units that ensure consistent execution across various environments [14]. This approach enhances applications' deployment, scaling, and management, as highlighted in [15]-[17]. Docker containers can address integration challenges in TPMS systems by enabling modular application development and efficient resource utilization, which are critical for ensuring reliability and scalability.

This study aims to address the limitations of traditional TPMS by developing a smart tire pressure and temperature monitoring system that integrates cloud computing and Docker container technologies. The proposed system facilitates real-time data transmission to a cloud server while leveraging Docker containers to streamline program integration and deployment. By enabling remote monitoring through smartphone applications, this system enhances safety and operational efficiency, offering a scalable and cost-effective

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solution for modern vehicles. Additionally, this study analyzes the implementation results to demonstrate how the proposed solution addresses existing gaps and advances the capabilities of TPMS.

II. RESEARCH METHODOLOGY

This paper outlines the essential stages in developing a smart tire pressure and temperature monitoring system utilizing cloud and Docker Container technology. As shown in Fig.1, the research involves key phases, including conducting a literature review, designing and implementing the system, testing its functionality, analyzing the findings, and drawing conclusions. Each step contributes to refining the system's performance and reliability. This chapter explains each phase, including the final analysis and conclusions summarizing the system's effectiveness.

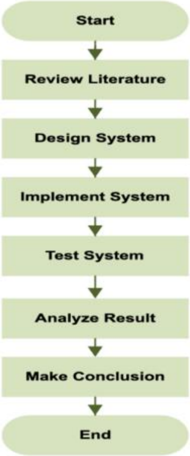

Fig.1 The Flow of The Research Method

A. Literature Review

TPMS has become an essential safety feature in vehicles. There are two main types of TPMS: direct system and indirect system [18]. Direct systems achieve precise tire pressure readings by installing individual sensors on each vehicle tire [8][9]. In contrast, indirect systems estimate tire pressure using sensors already built into the car, detecting pressure loss by monitoring changes in the recorded data. While indirect systems are more cost-effective since they use existing sensors, direct systems offer real-time, accurate pressure data for each tire [19]. By alerting drivers to potential pressure issues, TPMS plays a vital role in enhancing vehicle safety and preventing hazardous situations, thereby improving overall road safety.

Cloud technology in TPMS enhances real-time data processing, storage, and accessibility for vehicle operators and fleet managers [20][21]. Integrating TPMS with cloud platforms enables continuous monitoring, analysis, and transmission of tire pressure data to remote servers. The cloud enables users to access tire status remotely via mobile applications, improving safety and efficiency. The combination of TPMS and cloud services optimizes fleet management by providing centralized monitoring and automating alerts, thereby extending vehicle lifespan and reducing operational costs.

A Docker container is a lightweight, portable, and self-sufficient software package that includes all components required to execute an application, such as the code, runtime, system tools, libraries, and settings [22]. It facilitates efficient software installation and management by creating an isolated environment, allowing applications to run reliably across different development and production platforms [23]. This approach optimizes resource utilization while enabling the concurrent execution of multiple applications without interference [24].

B. Design System

This section outlines the system design for a Smart Tire Monitoring System for vehicles. The block diagram of the system is shown in Fig.2.

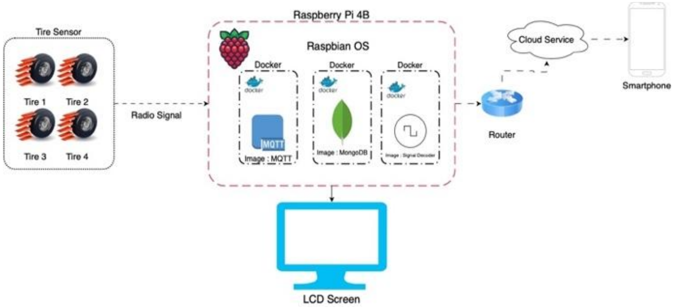

Fig.2 Block Diagram of System

In this system, four tire sensors are installed on the vehicle's wheels to monitor tire pressure and temperature continuously. Each sensor transmits encoded radio signals containing tire data at a frequency of 433 MHz. These signals are received by a Realtek RTL2832U-based radio receiver, which operates within a frequency range of 500 kHz to 1.766 MHz. The receiver is connected to the central controller, a Raspberry Pi 4B equipped with a Quadcore Cortex A-72 processor, Broadcom BCM2711 chipset, 2GB of RAM, and IEEE 802.11ac wireless capability. The radio signals are encoded to ensure secure and interference-resistant communication, and the system employs a signal decoder to process the received data. Frequency-Shift Keying (FSK) modulation is used in this system. FSK modulation is a digital modulation technique in which the frequency of a carrier signal is varied to represent binary data. It is widely used in communication systems, particularly for wireless transmission, due to its simplicity, robustness, and resistance to noise and interference. The decoded data is then translated into readable tire pressure values in kiloPascals (KPa) and temperature values in degrees Celsius (°C). Pressure is measured in Pascals (Pa), the standard unit defined as one Newton of force applied over an area of one square meter (N/m^2). This setup offers immediate access to tire pressure and temperature data, greatly enhancing driving convenience.

The central controller operates within a Docker container, which serves as a lightweight and portable environment to run the system's core software components. These components include the radio receiver application, which captures data

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transmitted from the tire sensors, and a MongoDB database, used for efficient local data storage. Additionally, the Docker container includes the Message Queuing Telemetry Transport (MQTT) protocol, a critical component for facilitating seamless communication between the local system and the cloud server.

The use of Docker offers several technical advantages. By encapsulating the software components and their dependencies, Docker ensures consistent behavior across various deployment environments, whether on a local machine, a server, or a cloud-based infrastructure. This consistency reduces system management's complexity and streamlines deployment and scaling processes. Furthermore, Docker's lightweight nature minimizes resource overhead, making it an ideal solution for IoT applications where system efficiency is paramount.

Once the radio receiver application receives the data from the tire sensors, it undergoes decoding to extract meaningful information such as tire pressure and temperature. The decoded data is then stored in MongoDB, which serves as a local archive for historical records. MongoDB's NoSQL structure is well-suited for handling sensor data's semi-structured and dynamic nature. After being stored locally, the data is transmitted to a cloud server using MQTT. This protocol, known for its lightweight and efficient design, is especially advantageous for IoT systems, as it minimizes bandwidth usage and ensures reliable data delivery even in environments with limited connectivity or resource-constrained devices.

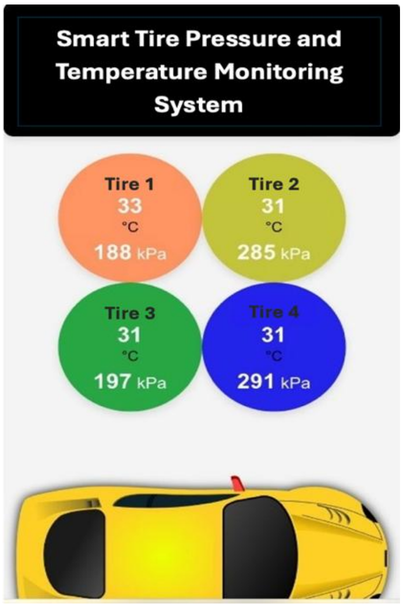

Fig.3 The Interface of Smart Tire Monitoring System on A Smartphone

Cloud-based data processing plays a critical role in the system's functionality. By leveraging cloud resources, the system enables real-time monitoring and data accessibility from remote locations. Users can interact with the smart tire monitoring system through two primary interfaces. They are a smartphone application and a browser-based web application. These interfaces provide an intuitive and user-friendly layout, displaying real-time key metrics such as tire pressure and temperature. As illustrated in Fig.3, the smartphone interface is designed to provide a clean and organized presentation of the data, ensuring that users can quickly interpret the information and make informed decisions.

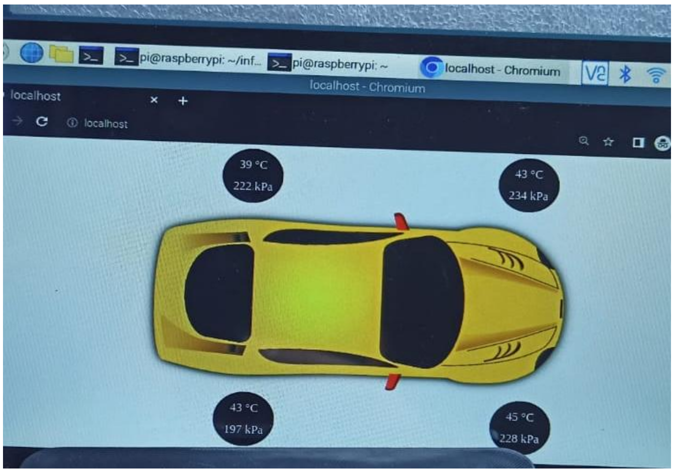

Fig.4 Display of LCD Screen

Additionally, tire data is displayed on a 7-inch Liquid Crystal Display (LCD) installed within the vehicle's dashboard, strategically placed for easy visibility by the driver. The LCD serves as a local interface, providing critical tire information such as pressure (in kiloPascals, kPa) and temperature (in degrees Celsius, °C). The graphical user interface (GUI) is built using HTML and operates within a browser-based application hosted on the vehicle's central controller. This approach leverages the Raspberry Pi's built-in web server capabilities to render the interface dynamically. Fig.4 illustrates the LCD, which incorporates numerical data and a schematic representation of the vehicle to visually map tire-specific readings to their respective positions on the vehicle. This design enhances user comprehension, ensuring drivers can quickly identify any anomalies in tire performance.

The browser application is optimized for real-time updates using WebSocket technology, enabling bidirectional communication between the application and the back-end system running on the Raspberry Pi. This ensures minimal latency in updating the tire data on the display as new information is received from the sensors. The application's modular design separates data retrieval, processing, and rendering logic, improving maintainability and scalability. For example, the back end retrieves decoded tire sensor data from MongoDB and formats it for display using Python scripts, while the front-end handles rendering and user interaction. The system's reliance on web technologies ensures compatibility and adaptability, making integrating additional features like historical data visualization or predictive analytics in future iterations feasible.

III. RESULT AND DISCUSSION

System testing was conducted using a four-wheeled multi-purpose vehicle (MPV) with one driver and three passengers.

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Testing was carried out during both day and night. The vehicle specifications are shown in Table I.

TABLE I
SPECIFICATION OF VEHICLE

Parameters	Value
Dimensions	Length: 439.5 cm Width: 173.0 cm Height: 166.5 cm
Engine Capacity	1,298 cc
Tire	185/65 R15

A. Testing results in the daytime

1) Tire Pressure Results

The vehicle tire pressure testing conducted during the day revealed varying pressure levels across the tires, which can be attributed to changes in the ambient temperature surrounding the vehicle. The tire pressure data is shown in Fig.5. Tire 1 has an average pressure of 233.1 kPa, gradually increasing from 228 kPa to 241 kPa. Tire 2 recorded an average pressure of around 231.4 kPa, showing slight fluctuations with a maximum value of 238 kPa. Tire 3 is more stable, with an average pressure of 223.7 kPa and a small variation from 222 kPa to 228 kPa. In contrast, Tire 4 recorded a lower pressure with an average of 192.7 kPa, experiencing a decrease from 203 kPa to 184 kPa. These differences, particularly in Tires 1 and 4, are most likely due to variations in surrounding temperature and road conditions that affect the pressure.

The standard deviation analysis provides further insight into the pressure stability of each tire. Tire 1 has a standard deviation of 4.5, indicating higher fluctuations than the other tires. Tires 2 and 3 have lower standard deviations, 3.2 and 1.8, respectively, showing better pressure consistency. Tire 4, with a standard deviation of 5.6, exhibits the greatest pressure variation, suggesting instability that may be caused by additional load or environmental influences. This standard deviation data indicates that Tires 1 and 4 have larger fluctuation levels, while Tire 3 appears to be the most stable in maintaining optimal pressure. These data serve as an important basis for further monitoring, particularly for tires that exhibit significant variation.

Regression analysis of the daytime pressure data provides additional insights into the trends in pressure change. Tire 1 has a positive regression coefficient, indicating a tendency for pressure to increase over time, likely due to heating from exposure to sunlight. Tire 4, on the other hand, shows a negative regression coefficient, indicating a downward pressure trend that could be related to a different response to temperature or road conditions. Meanwhile, Tires 2 and 3 have regression coefficients close to zero, indicating stable pressure without significant changes throughout the observation period. Overall, the combination of standard deviation and regression analyses suggests that Tires 1 and 4 may require further monitoring, as both exhibit significant pressure fluctuations that could affect vehicle safety and stability.

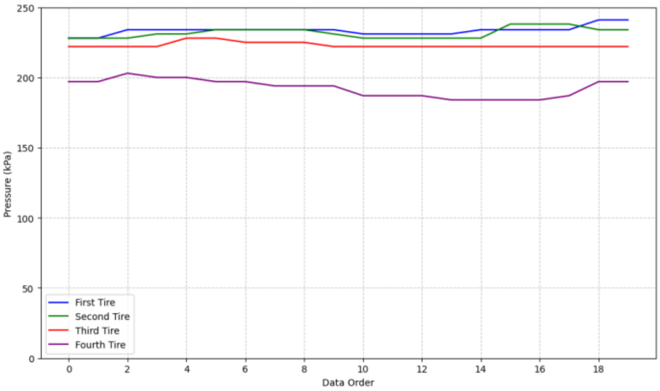

Fig.5 Results of Tire Pressure in Daytime

2) Tire Temperature Results

The tire temperature monitoring tests conducted during the day revealed significant temperature variations across the four tires. The tire temperature data is shown in Fig. 6. Tire 1 exhibited relatively stable temperatures with minor fluctuations, ranging from 39°C to 44°C, indicating that this tire is more resistant to environmental temperature changes. In contrast, Tire 2 exhibited larger temperature fluctuations, ranging from 39°C to 48°C, with a peak temperature of 48°C. This suggests the possibility of external factors, such as load or road conditions, affecting the tire's temperature. Tire 3 maintained the most consistent temperature, ranging from 36°C to 41°C, and tended to keep temperatures lower than the other tires, possibly due to material characteristics or better road conditions. Tire 4, on the other hand, demonstrated a more noticeable decrease in temperature, with a range of 33°C to 45°C, which could indicate a greater influence from external conditions, such as direct sunlight or more extensive wear on the tire.

Data analysis indicates that Tires 1 and 3 are more stable in maintaining optimal temperatures, while Tires 2 and 4 experience greater fluctuations. The higher temperature fluctuations in Tire 2 could be caused by higher air pressure, heavier loads, or rougher road conditions, which increase friction and generate higher temperatures. Conversely, the significant temperature drop in Tire 4 may be attributed to external environmental influences or different usage factors. This data emphasizes the importance of monitoring the temperature of tires that exhibit higher fluctuations, as excessive temperature changes can affect tire performance and longevity.

Further statistical analysis reveals the standard deviation, which measures the temperature distribution for each tire. Tire 1 has a standard deviation of 1.53, indicating relatively small temperature fluctuations. Tire 2 has a higher standard deviation of 2.34, suggesting greater temperature variation. Tire 3 has a standard deviation of 1.63, indicating moderate fluctuation, while tire 4, with a standard deviation of 3.28, shows the highest temperature variation among the four tires. This indicates that 4 tire experiences more drastic temperature changes than the other tires, which could suggest instability or imbalance in the tire's condition.

Tire 1 showed a regression coefficient close to zero in the regression analysis, indicating that the temperature remained stable, with no significant increase or decrease over time. Tire 2, with a positive regression coefficient, showed an upward temperature trend over time, indicating continuous heating during the test, likely due to external factors such as load or a hotter road surface. Tire 3 had a small negative regression coefficient, indicating a slight decrease or consistent temperature maintenance. Tire 4 showed a larger regression coefficient with a downward temperature trend, which could be due to the tire adapting more rapidly to changes in environmental temperature. Overall, this regression analysis confirms that Tires 2 and 4 require more attention regarding temperature stability to ensure vehicle performance and safety.

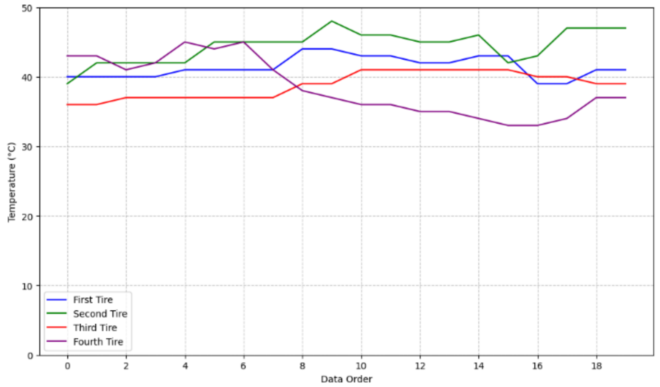

Fig.6 Results of Tire Temperature in Daytime

B. *Testing Results In Night-Time*

1) *Tire Pressure Results*

Testing of vehicle tire pressure at night showed slight variations in each tire's pressure, likely linked to ambient temperature stability under these conditions. The data on tire pressure is presented in Fig.7. Tire 1 recorded an average pressure of approximately 194.5 kPa, with a decrease to 181 kPa, while Tire 2 showed an average of 206.1 kPa, with a slight drop from 209 kPa to 200 kPa. Tire 3 recorded an average pressure of 197.2 kPa, gradually decreasing to 191 kPa, and Tire 4 remained relatively stable with an average of 196.35 kPa and a slight drop to 194 kPa. These fluctuations, especially in Tires 1 and 3, suggest the influence of road conditions or temperature changes, despite the pressure values remaining within safe limits. The variation in pressure among tires still requires attention, as it can affect vehicle stability, particularly at high speeds or when making turns.

Standard deviation analysis was conducted to evaluate the consistency of pressure in each tire. The results indicate that Tires 1 and 3 have standard deviations of 6.2 and 5.8, respectively, signifying greater pressure fluctuations than Tires 2 and 4, which showed lower standard deviations of 3.0 and 1.2, respectively. The higher standard deviations in Tires 1 and 3 reflect potential instability, possibly due to variable road conditions or temperature responses. Conversely, Tires 2 and particularly Tire 4 demonstrate better stability in maintaining optimal pressure throughout the observation period. These standard deviation values suggest that Tires 1 and 3 may require further inspection, while Tires 2 and 4 are more stable.

Regression analysis of tire pressure data adds insights into pressure change patterns over time, especially for Tires 1 and 3. A significant negative regression coefficient in these two tires indicates a trend of decreasing pressure, consistent with their high standard deviation values, highlighting a tendency for pressure decline under certain conditions. In contrast, Tires 2 and 4 exhibit regression coefficients close to zero, indicating stable pressure without significant change over time. This result helps identify Tires 1 and 3 as those requiring special monitoring, particularly if this trend continues in the long term, as it could indicate potential leakage or decline in tire performance. The regression and standard deviation analyses provide valuable information for maintenance decisions, supporting enhanced vehicle safety and stability.

Although the results confirm the system's ability to monitor tire pressure effectively, several limitations must be addressed to validate its performance fully. First, the influence of extreme environmental conditions, such as sub-zero temperatures or high heat, was not tested and may affect hardware reliability and sensor accuracy. The system's scalability for different vehicle types, including heavy-duty trucks or motorcycles, remains unexplored. A deeper comparison with other TPMS designs that leverage cloud and container technologies could provide insight into how this system performs in terms of data processing efficiency, reliability, and deployment flexibility.

From a practical perspective, the system offers a valuable solution for real-time tire pressure monitoring, particularly under stable night-time conditions. However, real-world factors such as vehicle type, load, and extreme weather conditions must be considered to ensure robust performance. Future research should focus on testing the system under diverse conditions and exploring enhancements to reduce pressure fluctuations and improve overall reliability. These steps will be crucial to establish the system's broader applicability and effectiveness in varied operational scenarios.

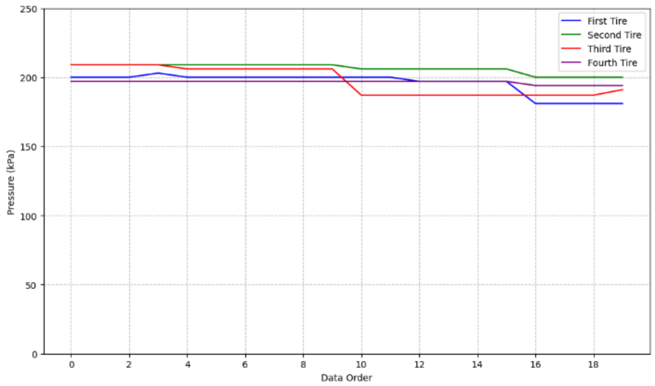

Fig.7 Results of Tire Pressure in Night-Time

2) *Tire Temperature Results*

The results of the tire temperature monitoring conducted at night show varying temperature patterns across the four tires. The data on tire temperature is presented in Fig.8. Tire 1 has a

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relatively stable temperature, ranging from 26°C to 35°C, with the lowest values observed in the later stages of testing. This could indicate that the tire was exposed to lower environmental temperatures as the night progressed or could result from decreased activity. Tire 2 displays a steady temperature between 32°C and 37°C, with minor fluctuations. This suggests that the tire maintained a relatively consistent temperature, possibly due to the tire's design or the moderate environmental conditions at night. Tire 3, however, shows more significant fluctuations, ranging from 25°C to 37°C. These fluctuations may be attributed to external factors such as different areas of exposure to temperature or changes in road conditions during the testing period. Lastly, Tire 4 exhibits a temperature range from 32°C to 36°C, indicating stability in its performance, with some slight variations in the earlier measurements that could be linked to initial conditions.

Data analysis suggests that Tire 1 experienced the largest temperature decrease, particularly towards the latter part of the testing period. It may indicate that it was exposed to cooler night conditions or had less friction due to reduced driving activity. Tire 2, on the other hand, displayed the least fluctuation, maintaining a more consistent temperature, possibly due to better insulation or a more stable interaction with the road surface. Tire 3's fluctuations, particularly the sharp drop to 25°C, suggest that external conditions, such as road temperature or exposure to wind, played a significant role in its performance. Tire 4, with relatively stable temperatures, reflects a balance between environmental conditions and tire efficiency.

The standard deviation analysis indicates varying temperature fluctuations across the tires. Tire 1 has the lowest standard deviation, around 1.44, suggesting smaller temperature fluctuations. Tire 2 has a slightly higher standard deviation of approximately 1.42, indicating slightly greater but relatively stable temperature fluctuations. Tire 3 has the highest standard deviation, approximately 3.21, indicating larger temperature variations and higher volatility, which may be attributed to external factors such as varying road conditions or air pressure. Tire 4 has a standard deviation of 1.23, indicating more controlled temperature fluctuations and greater consistency.

In the regression analysis, Tire 1 has a slight negative regression coefficient, indicating a gradual decrease in temperature over time, which is consistent with the natural cooling that occurs at night. Tire 2, with a near-zero regression coefficient, shows no significant trend, implying that the tire's temperature remained relatively stable throughout the testing period. Tire 3, which displayed more substantial fluctuations, has a negative regression coefficient, suggesting that its temperature decreased over time, likely due to cooling effects during the night or external temperature factors. Tire 4's regression coefficient also points to stability, with only minor fluctuations observed, confirming that the tire maintained a steady temperature. Overall, this analysis highlights the impact of external environmental factors, such as night-time cooling and road conditions, on tire temperature, indicating that Tire 2 and Tire 4 performed more consistently under these conditions.

While the results indicate that the system effectively captures temperature data and provides valuable insights into tire behavior, some limitations must be addressed. For instance, environmental constraints such as extreme weather conditions or rapid temperature changes could impact the system's performance and reliability. The system's scalability for different vehicle types, including larger commercial fleets or vehicles with varying tire specifications, remains untested. A comparison with other TPMS designs leveraging cloud and container technologies could further validate the system's advantages in terms of data accuracy, real-time monitoring, and deployment efficiency.

From a practical perspective, the findings suggest that the proposed system is suitable for night-time operations under moderate conditions, offering stable and reliable monitoring. However, further studies should explore the impact of extreme conditions, such as snow, rain, or heat waves, on the system's hardware and software performance. Addressing these factors will be critical to ensuring the system's robustness and broad applicability in real-world scenarios.

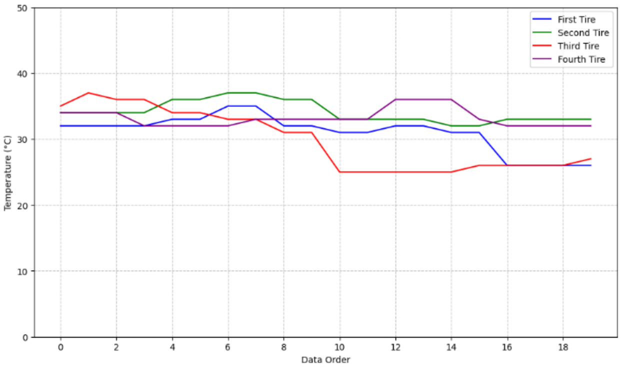

Fig.8 Results of Tire Temperature at Night-Time

IV. CONCLUSION

Tire blowouts are a common cause of vehicle accidents, often occurring when drivers continue operating their vehicles despite tire pressure and temperature exceeding safe limits. This paper introduces a vehicle tire pressure and temperature monitoring system that utilizes Cloud and Docker Container technology to address this issue. The system provides tire pressure and temperature data on multiple platforms, such as LCD screens, computers, and smartphones, and effectively monitors fluctuations in tire conditions through real-time tracking. Testing was carried out both during the day and at night. The results indicate that the optimal standard deviation for tire pressure during the day is 1.8, whereas at night, it is 1.2. The optimal standard deviation for tire temperature is 1.54 during the day and 1.23 at night, indicating relatively low variability in pressure and temperature. This system is crucial for improving vehicle safety and reducing accidents caused by tire-related issues. The proposed system's unique contributions lie in integrating cloud computing and containerization technologies to improve scalability, data accessibility, and deployment efficiency. This design aligns with the needs of industry stakeholders, including automotive manufacturers and

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fleet operators, by providing a reliable and cost-effective solution for tire condition monitoring. However, implementing the system in real-world applications presents several potential challenges, including the cost of hardware, technical barriers related to data security and reliability, and environmental constraints such as extreme weather conditions. Future research will address these challenges and expand the system's functionality, such as incorporating vehicle location tracking and predictive analytics for proactive maintenance. By addressing these areas, the system can be further refined to meet the demands of diverse operating environments, paving the way for broader adoption in the automotive and transportation industries.

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