

Real-Time Wireless Tyre Pressure Monitoring System (TPMS) for Enhanced Vehicle Safety

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Abstract— The Automatic Tyre Pressure Monitoring System (TPMS) is an advanced safety and efficiency-enhancing system designed to continuously monitor the air pressure in vehicle tyres. It utilizes pressure sensors installed within the tyres to detect pressure variations and transmits real-time data wirelessly to a dashboard display or a mobile application. Upon detecting deviations from the optimal pressure range, the system promptly alerts the driver, enabling timely corrective action. By ensuring proper tyre inflation, TPMS enhances road safety, fuel efficiency, and tyre longevity, reducing the risks associated with underinflated or over-inflated tyres, such as blowouts and increased wear. The system operates using direct or indirect monitoring methods—direct TPMS employs dedicated pressure sensors, while indirect TPMS utilizes wheel speed data from the Anti-lock Braking System (ABS) to estimate pressure changes. The implementation of TPMS contributes to enhanced vehicle performance, reduced maintenance costs, and lower environmental impact by optimizing fuel consumption and minimizing carbon emissions. This system is an essential feature in modern automobiles, promoting safer and more efficient driving conditions.

Keywords—Tyre Pressure Monitoring System (TPMS), Pressure Sensors, Real-time Monitoring, Road Safety, Fuel Efficiency

I. INTRODUCTION

The Tyre Pressure Monitoring System (TPMS) is a crucial safety technology in modern vehicles, designed to continuously monitor tyre pressure and alert drivers if it drops below the recommended level. Proper tyre inflation is essential for safe driving, improved fuel efficiency, and extended tyre lifespan. A sudden loss of pressure can lead to dangerous situations such as tyre blowouts, reduced vehicle stability, and increased stopping distances. TPMS plays a vital

role in preventing such issues by ensuring that drivers are informed about their tyre conditions in real time.

There are two main types of TPMS: Direct TPMS and Indirect TPMS. Direct TPMS consists of pressure sensors installed inside each tyre, which measure the air pressure and transmit the data to the vehicle's onboard system. When the pressure falls below a certain threshold, a warning light appears on the dashboard. This type of system provides precise and real-time readings. Indirect TPMS, on the other hand, does not use dedicated pressure sensors. Instead, it relies on the vehicle's Anti-lock Braking System (ABS) and wheel speed sensors to detect differences in tyre rotation. A tyre with low pressure will have a slightly different rotational speed compared to properly inflated tyres, which the system detects and interprets as a possible under inflation issue.

The benefits of TPMS extend beyond just safety. Maintaining proper tyre pressure improves fuel efficiency, as underinflated tyres create more rolling resistance, requiring more energy to move the vehicle forward. It also helps reduce tyre wear and tear, saving drivers from frequent tyre replacements and unnecessary expenses. Additionally, by optimizing fuel usage, TPMS indirectly helps in reducing carbon emissions, contributing to environmental sustainability.

With technological advancements, TPMS is becoming increasingly sophisticated. Some modern vehicles are equipped with advanced TPMS systems that provide detailed pressure readings for each tyre and integrate with smartphone apps for remote monitoring. As many governments worldwide enforce regulations requiring TPMS in all new vehicles, this system is expected to become a universal standard for road safety. The adoption of TPMS ensures that drivers are real ways aware of their tyre conditions, leading to safer, more efficient, and environmentally friendly driving experience.

The literature review provides an in-depth analysis of the research, technological developments, regulatory standards, and advancements in the Automatic tyre Pressure Monitoring System (TPMS). It explores the evolution of TPMS, different types of monitoring systems, key components, challenges, and emerging trends in the field. The review is crucial for understanding how TPMS contributes to vehicle safety, fuel efficiency, and predictive maintenance.

The concept of TPMS emerged due to the increasing number of road accidents caused by underinflated tyres. The development of TPMS followed several key milestones:

1980s: TPMS was first introduced in luxury European vehicles to improve driving safety and performance[1].

2000s: The U.S. implemented the TREAD Act (2000), which mandated the inclusion of TPMS in all new vehicles sold after 2007.

2010s - Present: TPMS has evolved with smart vehicle technologies, IoT integration, and AI-driven predictive maintenance systems for enhanced real-time monitoring.

Regulatory Standards and Requirements

Governments worldwide have mandated TPMS to enhance road safety and reduce fuel consumption:

United States: The TREAD Act (2000) by the National Highway Traffic Safety Administration (NHTSA) made TPMS mandatory in all vehicles from 2007 onwards [2].

European Union: The ECE-R64 regulation (2014) requires TPMS in all newly manufactured passenger vehicles.

China, Japan, and Other Countries: National safety regulations encourage TPMS adoption to minimize vehicle-related accidents and optimize fuel economy.

TPMS can be classified into two main types based on their working principles: D.1 Direct TPMS (dTPMS) uses individual pressure sensors inside each tyre to provide real-time pressure readings. Offers high accuracy but is more expensive due to the hardware components. Can detect gradual pressure loss and sudden punctures effectively. D.2 Indirect TPMS (iTPMS) relies on the vehicle's Anti-lock Braking System (ABS) sensors to estimate pressure variations by monitoring wheel speed differences. Less expensive but less accurate, as it does not measure pressure directly. Mainly detects anomalies rather than precise pressure values.

Components and Working Principles of TPMS

A Direct TPMS (dTPMS) consists of the following key components:

(i) Pressure Sensors: Installed inside tyres to continuously measure air pressure. (ii) Wireless Transmitters: Send real-time data to the vehicle's Electronic Control Unit (ECU). (iii) Control Unit (ECU): Analyzes pressure readings and triggers alerts when tyre pressure drops below the threshold. (iv) Dashboard Display & Alerts: Notifies drivers of abnormal tyre pressure conditions.

An Indirect TPMS (iTPMS) estimates tyre pressure loss using the ABS wheel speed sensors, detecting variations in rotational speeds to infer pressure loss.

Studies show that TPMS plays a crucial role in: (i) Improving Road Safety: Research indicates that underinflated tyres contribute to approximately 40% of tyre-related accidents. TPMS helps prevent these by maintaining optimal pressure levels. (ii) Enhancing Fuel Efficiency: Properly inflated tyres can increase fuel efficiency by 3-5%, reducing unnecessary fuel consumption.

Despite its advantages, TPMS faces several challenges in implementation. (i) Sensor Accuracy Issues: Environmental conditions such as temperature fluctuations and sensor placement can affect accuracy. (ii) Battery Life Constraints: Most TPMS sensors require battery replacements, increasing maintenance costs. (iii) Cost-effectiveness: The high cost of direct TPMS discourages widespread adoption, especially in low-cost vehicles. (iv) Environmental Impact: Disposal of TPMS sensors and batteries poses environmental challenges, prompting research into self-powered TPMS solutions.

Advancements in TPMS Technology

Modern TPMS systems are evolving with cutting-edge technology, making them more efficient and intelligent. Some key advancements include: (i) Smart TPMS Integration with the Internet of Things (IoT) allows TPMS data to be accessed via cloud-based systems and mobile applications for remote monitoring. (ii) Self-Powered TPMS: New research focuses on energy harvesting techniques (e.g., piezo electric sensors, RF energy harvesting) to eliminate the need for battery replacements, making TPMS systems more sustainable. (iii) AI-Based Predictive Maintenance: Machine learning algorithms analyze tyre pressure trends to predict potential failures before they occur. (iv) Deep learning models such as Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) are used to enhance predictive analytics.

Pattern recognition plays a crucial role in identifying abnormal tyre pressure conditions and preventing failures. Various approaches are used to analyze sensor data: (i) Statistical Models: Utilize historical tyre pressure data to establish normal trends and predict gradual pressure loss. (ii) Machine Learning Techniques: Algorithms such as Support Vector Machines (SVM) and Decision Trees classify normal and abnormal tyre pressure patterns. (iii) Neural Networks: Deep learning models, including CNNs and RNNs, help detect real-time pressure variations and improve accuracy overtime. Template Matching Techniques: Compare current tyre pressure data with predefined normal patterns to quickly detect anomalies.

II. METHODOLOGY

The methodology of the tyre Pressure Monitoring System (TPMS) involves a structured approach to system design, data acquisition, and signal processing to ensure accurate and real-time pressure monitoring. [4] The first step is selecting the appropriate TPMS type, either Direct TPMS (dTPMS), which uses pressure sensors inside each tyre, or Indirect TPMS (iTPMS), which relies on wheel speed sensors to estimate pressure variations. Once the type is chosen, the system's hardware components are identified, including pressure sensor (hx710b) for real-time monitoring (Fig.1), a microcontroller (ESP32) for data processing (Fig.2), a wireless

transmitter for communication, a battery powered supply, and a display unit for user alerts.

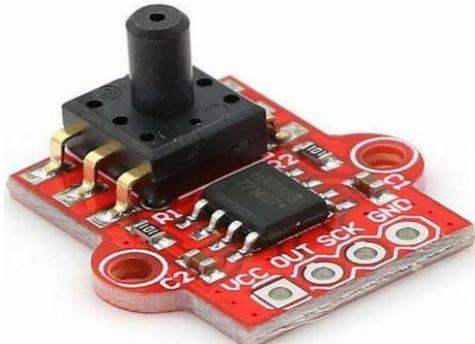


Fig.1 HX710B pressure sensor

In the data acquisition phase, pressure sensors continuously measure tyre pressure and temperature, transmitting this data to the ECU. The ECU processes the collected data, filtering out noise and identifying deviations from normal pressure levels. If an anomaly is detected, such as a sudden drop in pressure, the system activates an alert through the dashboard display or external communication interfaces. The TPMS may also integrate pattern recognition techniques, such as statistical models, machine learning, or neural networks, to enhance accuracy and predict potential failures. The final stage involves system calibration and testing, ensuring the TPMS functions reliably under different environmental conditions. By following this methodology, TPMS enhances vehicle safety, reduces tyre wear, and prevents accidents caused by underinflated or overinflated tyres.

Sensor Selection and Placement in TPMS

The selection and placement of sensors in a tyre Pressure Monitoring System (TPMS) are crucial for ensuring accurate pressure measurement and efficient system performance. In Direct TPMS (dTPMS), pressure sensors are used to measure real-time air pressure inside each tyre,[5] while temperature sensors help compensate for pressure variations due to heat. These sensors are typically MEMS-based for higher accuracy and lower power consumption. Additionally, wireless transmitters are integrated to send sensor data to the Electronic Control Unit (ESP32), and they are powered by long-lasting batteries to ensure continuous operation. In contrast, Indirect TPMS (iTPMS) does not use direct pressure sensors but instead relies on wheel speed sensors (ABS sensors) to estimate pressure variations based on rotational differences among tyres. Some advanced indirect systems also use accelerometers to detect sudden changes in tyre behavior.

Sensor placement is equally important for reliable operation. In Direct TPMS, sensors are typically mounted inside the tyre and attached to the valve stem or embedded within the wheel assembly to prevent external damage and tampering. This internal placement ensures precise measurements and protects the sensors from environmental factors such as dirt, moisture, and road debris.[3] In Indirect TPMS, the wheel speed sensors are integrated into the vehicle's existing ABS system, usually positioned near the wheel hub, where they continuously monitor rotational speed

variations. Proper sensor placement not only enhances measurement accuracy but also ensures that the system functions efficiently, providing timely alerts to the driver in case of abnormal tyre pressure.

Wireless Communication in TPMS

Wireless communication is a fundamental aspect of tyre Pressure Monitoring Systems (TPMS), enabling real-time data transfer between tyre sensors and the vehicle's Electronic Control Unit (ECU). Instead of using wired connections, TPMS sensors rely on radio frequency (RF) signals, typically operating at 315 MHz or 433 MHz, to transmit tyre pressure and temperature data. This ensures seamless communication while maintaining a low power consumption, making it ideal for vehicle applications. In modern TPMS, Bluetooth Low Energy (BLE) is also being integrated, allowing drivers to monitor tyre conditions directly from their smartphones via dedicated mobile apps.

The wireless TPMS system works by continuously measuring tyre pressure and sending this data to the ECU. The ECU processes the received information and checks for deviations from normal pressure levels. If the pressure drops below a safe threshold, the system triggers a warning on the vehicle's dashboard. In smart TPMS systems, wireless connectivity extends beyond the vehicle, enabling remote monitoring through cloud-based platforms or mobile applications. This is particularly beneficial for fleet management, where multiple vehicles need real time monitoring.

One of the key advantages of wireless TPMS is its elimination of complex wiring, reducing installation and maintenance costs. Additionally, it provides faster response times and enhances vehicle safety by immediately detecting underinflation or potential tyre failures. However, wireless communication faces challenges such as signal interference from other RF sources, limited sensor battery life, and potential security risks from unauthorized signal interception. These challenges can be mitigated by using encrypted communication protocols and energy efficient sensors.



Fig.2 ESP32 Microcontroller

Overall, wireless communication in TPMS significantly improves driving safety, fuel efficiency, and tyre lifespan by providing accurate, real-time monitoring. With advancements in IoT and AI-based systems, future TPMS

solutions will become even smarter, allowing vehicles to predict tyre failures and integrate seamlessly with other automotive safety features.

Data Processing and Alert System in TPMS

The tyre Pressure Monitoring System (TPMS) relies on efficient data processing and alert mechanisms to ensure accurate and timely warnings about tyre pressure abnormalities. Once the pressure and temperature sensors collect real-time data, it is transmitted wirelessly to the Electronic Control Unit (ECU). [7] The ECU acts as the system's central processor, filtering and analyzing the received data to detect pressure deviations, sudden drops, or slow leaks. Advanced TPMS may also use machine learning algorithms to distinguish between normal pressure fluctuations (due to temperature changes) and actual pressure loss caused by leaks or punctures.

The data processing system compares sensor readings against predefined pressure thresholds set by manufacturers or users. If the measured pressure falls below or exceeds the safe range, the ECU categorizes the issue based on severity. For minor pressure losses, a low-pressure warning is generated, while for critical conditions like a sudden puncture, an immediate hazard alert is triggered. Some modern TPMS also incorporate predictive analysis, using past data trends to warn drivers about potential future tyre failures before they occur.

Once the ECU detects an abnormal condition, the TPMS activates its alert mechanism. Most vehicles display a warning indicator light on the dashboard, often represented by a yellow tyre symbol with an exclamation mark. Some advanced systems provide detailed messages on digital screens, specifying which tyre is affected and the exact pressure value. In smart TPMS solutions, the alerts can be sent to smartphone apps or even fleet management systems, allowing remote monitoring and preventive maintenance[8].

The effectiveness of TPMS data processing and alert systems ensures that drivers receive timely warnings to take corrective action, preventing accidents, improving fuel efficiency, and extending tyre life. As technology advances, AI driven TPMS will enhance accuracy, reduce false alarms, and integrate seamlessly with connected vehicle networks, making driving safer and more efficient.

III. RESULT AND DISCUSSION

Accuracy and Reliability of TPMS

The accuracy and reliability of a tyre Pressure Monitoring System (TPMS) are crucial for ensuring vehicle safety and optimal tyre performance. Direct TPMS (dTPMS), which uses individual pressure sensors inside the tyres, is generally more accurate than Indirect TPMS (iTPMS), which estimates pressure based on wheel speed variations. dTPMS can measure real-time tyre pressure with an accuracy of ± 1 psi (pound per square inch), whereas iTPMS may have higher

errors due to external factors like uneven road surfaces, tyre wear, or temperature fluctuations[6].

Several factors influence TPMS accuracy, including sensor quality, calibration, and environmental conditions. High-quality MEMS-based sensors provide precise pressure readings, but over time, sensor degradation and battery limitations can affect accuracy. Temperature changes also impact pressure readings, as air expands when heated and contracts when cooled, potentially leading to false alerts if the system is not temperature-compensated. Advanced TPMS models use temperature-adjusted algorithms to minimize such errors and improve reliability.

Reliability in TPMS depends on consistent data transmission and effective alert mechanisms. Wireless communication in TPMS can sometimes experience signal interference, leading to temporary data loss or delays in transmitting pressure information to the ECU. To improve reliability, modern systems incorporate redundancy measures, such as multiple data transmission attempts or self-checking diagnostics, which verify sensor functionality and alert the driver if a sensor fails. Additionally, regular sensor calibration and system updates ensure long-term accuracy. Overall, the effectiveness of TPMS depends on both hardware precision and software processing. As technology advances, AI-based predictive maintenance and machine learning algorithms are being integrated into TPMS to enhance accuracy, reduce false alarms, [9] and improve reliability. These improvements will help ensure that drivers receive real-time, precise alerts, reducing the risk of tyre-related accidents and improving vehicle efficiency.

Impact of TPMS on Fuel Efficiency and tyre Life

A tyre Pressure Monitoring System (TPMS) plays a significant role in improving fuel efficiency and extending tyre life by ensuring that tyres remain properly inflated. Underinflated tyres increase rolling resistance, requiring the engine to use more fuel to maintain speed. Studies suggest that a 10% drop in tyre pressure can lead to a 2% decrease in fuel efficiency, directly affecting overall vehicle mileage. By continuously monitoring and alerting drivers about low tyre pressure, TPMS helps maintain optimal inflation, reducing fuel consumption and lowering CO₂ emissions[10].

Proper tyre pressure also significantly impacts tyre longevity. Underinflated tyres experience uneven tread wear, leading to premature deterioration, while overinflated tyres can cause excessive wear in the center of the tread. TPMS prevents these issues by ensuring that tyres remain within the recommended pressure range, promoting even wear and extending tyre lifespan by up to 20%. This not only reduces replacement costs but also enhances road safety by maintaining better traction and stability.

In addition to direct benefits, TPMS contributes to vehicle performance and safety. Properly inflated tyres improve handling, braking efficiency, and heat dissipation, reducing the risk of tyre blowouts. For fleet vehicles and commercial transport, TPMS helps in predictive maintenance, preventing unexpected tyre failures and minimizing downtime[11].

Overall, TPMS is a crucial system that enhances both economic and environmental benefits. By maintaining the right tyre pressure, it reduces fuel costs, lowers carbon emissions, increases tyre durability, and improves overall driving safety, making it an essential feature in modern vehicles.

Comparison of TPMS with Existing Technologies

Tyre Pressure Monitoring Systems (TPMS) are designed to ensure optimal tyre pressure, but other technologies like manual pressure gauges, nitrogen inflation, and run-flat tyres also contribute to tyre health and vehicle safety. Comparing TPMS with these existing technologies highlights its advantages and limitations.

1. ATPMS vs. Manual tyre Pressure Gauges

Manual Pressure Gauges require drivers to check tyre pressure manually at regular intervals. TPMS offers real-time, automated monitoring, reducing the risk of human error or negligence. While manual gauges provide accurate readings when used correctly, TPMS ensures continuous monitoring and instant alerts for pressure loss.

2. ATPMS vs. Indirect Monitoring (ABS-Based Systems)

Indirect TPMS (iTPMS) relies on ABS wheel speed sensors to estimate pressure changes, whereas Direct TPMS (dTPMS) uses dedicated pressure sensors inside the tyres. dTPMS is more accurate, as it provides exact pressure readings, while iTPMS only detects relative changes and may produce false alerts due to road conditions or tyre rotations. dTPMS can monitor each tyre individually,[12] whereas iTPMS only detects overall pressure loss in one or more tyres.



Fig.3 Hardware set-up

Fig.3 shows the tyre pressure monitoring system in real-time using the HX710B pressure sensor interfaced with an ESP32 microcontroller.[13] The HX710B sensor reads the tyre pressure and transmits the data to the ESP32. Through a Wi-Fi connection, the ESP32 sends the pressure readings to the Blynk IoT platform, allowing users to remotely monitor the tyre pressure through a mobile application.

To ensure vehicle safety and improve performance, a threshold pressure value is predefined in the system. When the detected tyre pressure drops below this threshold, the ESP32 triggers a buzzer to alert the user immediately. This early warning system helps prevent accidents, ensures optimal tyre life, and enhances fuel efficiency by maintaining proper tyre pressure.

IV. CONCLUSION

The tyre Pressure Monitoring System (TPMS) is a crucial technology that enhances vehicle safety, fuel efficiency, and tyre longevity.[14] By continuously monitoring tyre pressure and providing real-time alerts, TPMS helps prevent underinflation-related issues such as increased fuel consumption, uneven tyre wear, and potential blowouts. Compared to traditional tyre maintenance methods, TPMS offers automated, accurate, and reliable monitoring, reducing the need for manual pressure checks and minimizing human error.

The Integration of wireless communication, advanced sensors, and predictive analytics has further improved the effectiveness of TPMS, making it a key feature in modern vehicles.[15] Its impact on fuel savings, reduced carbon emissions, and cost-effective tyre maintenance highlights its significance not only for individual drivers but also for fleet management and commercial transport.

Despite challenges such as sensor calibration, battery life, and potential signal interference, continuous advancements in AI-based diagnostics and IoT-enabled TPMS solutions are enhancing system accuracy and reliability. As automotive technology evolves, TPMS will likely become even more sophisticated, integrating with smart vehicle systems for predictive maintenance and enhanced road safety.

In conclusion, TPMS is a valuable innovation that plays a vital role in improving driving safety, reducing operational costs, and promoting environmental sustainability. Its widespread adoption ensures that vehicles remain efficient, well-maintained, and safer for both drivers and passenger.

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