KeAi CHINESE ROOTS GLOBAL IMPACT
International Journal of Innovation Studies

A REAL-TIME IOT-BASED INTELLIGENT VEHICLE MONITORING SYSTEM FOR SUSTAINABLE TRANSPORTATION

Jeevanantham K
III BCA, Department of Computer Applications, Nehru Arts and Science College, Coimbatore, India, Jeevananthamk17@gmail.com

Navaneenth S
III BCA, Department of Computer Applications, Nehru Arts and Science College, Coimbatore, India, navaneethsivakumar8@gmail.com

Aswin M
III BCA, Department of Computer Applications, Nehru Arts and Science College, Coimbatore, India, aswinmohanann@gmail.com

Dr. A. Kalaivani
Associate Professor, Department of Computer Applications, Nehru Arts and Science College, Coimbatore, India, nasckalaivani@nehrucolleges.com

Abstract

Vehicular safety, operational efficiency, and predictive maintenance are major challenges in modern transportation systems, particularly in high-density urban environments and long-distance fleet operations. Traditional vehicle monitoring methods rely on periodic manual inspections and reactive diagnostics, which often result in delayed fault detection, higher maintenance costs, and safety risks. To overcome these limitations, this study proposes an Internet of Things (IoT)-based Smart Vehicle Monitoring System that enables continuous, real-time vehicular telemetry and intelligent diagnostics. To address these limitations, this study proposes an Internet of Things (IoT)-based Smart Vehicle Monitoring System that enables continuous, real-time monitoring of vehicle performance. The proposed architecture employs an ESP32 microcontroller integrated with multiple sensors to measure engine temperature, fuel level, vibration, GPS-based location, accelerometer-based motion, and environmental parameters such as ambient temperature and humidity. This intelligent monitoring approach enhances transportation safety and operational efficiency while supporting smart mobility and resilient infrastructure, contributing to Sustainable Development Goal (SDG) 9: Industry, Innovation and Infrastructure and SDG 11: Sustainable Cities and Communities.

To improve vehicle condition assessment, the system introduces a Vehicle Health Index (VHI) model developed using min–max normalization and a weighted multi-sensor data fusion technique. Unlike traditional threshold-based alert mechanisms, the proposed framework evaluates the combined influence of mechanical stress indicators and environmental conditions to generate a comprehensive health score. This score reflects real-time vehicle stability, maintenance priority, and operational risk..

Key Words: Internet of Things (IoT), Smart Vehicle, GPS Tracking, GSM Module, Real-Time

Monitoring, Vehicle Diagnostics, Sensors, Cloud Computing, Remote Monitoring, Data Analytics, Fleet Management, Accident Detection

Introduction

The maintenance of optimal vehicular performance and operational stability is a fundamental requirement for modern transportation systems. Precise monitoring of mechanical subsystems such as engine temperature, fuel efficiency, vibration patterns, and electrical performance is essential to ensure safety, reliability, and cost-effective operation. In contemporary mobility ecosystems characterized by dense traffic, extended logistics routes, and high utilization rates, vehicles are subjected to continuous mechanical stress and environmental variability. Prolonged exposure to such stressors without timely diagnostics can result in performance degradation, unexpected breakdowns, increased fuel consumption, and elevated safety risks.

Traditional vehicle maintenance methodologies predominantly rely on periodic inspections and reactive fault detection mechanisms. While effective to a limited extent, these approaches lack continuous monitoring capabilities and fail to provide early-stage predictive insights. Consequently, minor mechanical anomalies may escalate into critical failures before intervention occurs.

Background

Vehicular operational stability is not a static condition but a dynamic mechanical state influenced by continuous internal subsystem interactions and external environmental exposure. A vehicle's performance depends on the coordinated functioning of its engine, transmission, braking system, electrical circuits, and fuel delivery mechanisms. Even minor deviations in parameters such as engine temperature, vibration amplitude, or fuel consumption patterns can indicate early mechanical stress. If left undetected, these deviations may escalate into severe system failures, increased emissions, and compromised passenger safety.

Mechanical degradation is often accelerated by environmental factors. High ambient temperatures contribute to overheating risks, while elevated humidity and atmospheric variability can influence combustion efficiency and electrical reliability.

Related works

GPS-Based Vehicle Tracking Systems

Early research focused on integrating GPS modules with GSM communication to provide real-time vehicle location tracking. These systems were primarily designed for theft detection and fleet monitoring but lacked mechanical health diagnostics.

GSM Alert-Based Monitoring

Several systems incorporated GSM modules to send SMS alerts during accidents, overspeed, or unauthorized vehicle movement. While effective for emergency notification, these systems did not provide continuous health assessment.

OBD-II Integrated Diagnostic Systems

Later studies utilized On-Board Diagnostics (OBD-II) interfaces to extract engine parameters such as RPM, coolant temperature, and fault codes. These solutions improved engine monitoring but remained reactive, triggering alerts only after fault thresholds were crossed.

Research Category	**Primary Parameter**	**Sensing** Modality	Real-Time?	Hydration Specific?	Hard ware Cost
Vital Sign Monitors	HR, SpO_2, Body Temp	PPG Sensors	Yes	No	Low
Sweat Biosensors	Na^{+},K+ Concentration	Electrochemical Sensors	Limited	Yes	High
Environmental WBGT	Ambient Temp,Humidity	Fixed / Ambient	Yes	No (Heat Stress only)	Moderate

Problem statement

Vehicular malfunction and unexpected mechanical failure represent critical yet frequently underestimated operational risks in modern transportation systems, particularly in high-density urban mobility, long-haul logistics, and industrial fleet operations. Under conditions of prolonged usage, elevated ambient temperatures, variable humidity, and sustained mechanical load, vehicle subsystems experience progressive thermal stress, component wear, and efficiency degradation. Delays in identifying these early-stage anomalies often result in sudden breakdowns, increased fuel consumption, costly repairs, and potentially hazardous on-road incidents.

Traditional vehicle maintenance strategies rely predominantly on periodic servicing schedules, dashboard warning indicators, and reactive fault diagnostics through On-Board Diagnostic (OBD) systems. While these mechanisms provide essential feedback, they are inherently threshold-driven and reactive in nature. Minor deviations in engine temperature, vibration amplitude, or fuel efficiency frequently remain undetected until they escalate into critical failures.

Proposed System Hardware Architecture

The proposed smart vehicle monitoring framework integrates multi-modal sensing modules with a centralized embedded processing unit to enable low-latency vehicular telemetry and predictive diagnostics. The hardware architecture is designed to ensure real-time data acquisition, power efficiency, scalability, and cost-effectiveness while maintaining reliable operational accuracy for transportation environments.

Central Processing Unit: ESP32 Microcontroller

The core of the proposed system architecture is the **ESP32 microcontroller**, high-performance dual-core processor optimized for IoT applications. It functions as the primary computational node, responsible for real-time sensor data acquisition, normalization, and Vehicle Health Index (VHI) computation.

A. Mechanical and Operational Sensing Modules

1. Engine Temperature Sensor

Engine thermal stability is monitored using a precision temperature sensor interfaced with the engine block or coolant system. Abnormal temperature rise is a primary indicator of mechanical overload, cooling inefficiency, or lubrication failure. Continuous monitoring enables early detection of overheating risks.

2. Vibration Sensor Module

Mechanical imbalance and component wear are quantified using a vibration sensor (accelerometer-based module). Variations in vibration amplitude and frequency patterns are anto identify potential misalignment, bearing failure, or structural stress within the engine assembly.

Working Methodology

The operational framework of the proposed Smart Vehicle Monitoring System follows a structured sequential data acquisition and fusion pipeline, designed to convert raw mechanical and environmental telemetry into a quantifiable Vehicle Health Index (VHI). The progression from raw signal capture to actionable risk alerts is executed in real time within the embedded processing unit. The methodology is divided into four major phases: **Signal Acquisition, Data Pre-processing, Algorithmic Fusion, and Telemetry Transmission**.

A. Multi-Modal Signal Acquisition

The system begins by concurrently polling all integrated mechanical and environmental sensors. During the initialization phase, the ESP32 microcontroller establishes communication with each sensing module and begins continuous data acquisition.

- The **engine temperature sensor** captures thermal readings from the engine block or coolant system.
- The **vibration sensor (accelerometer module)** records oscillation amplitude and frequency patterns to detect mechanical imbalance.

B. Data Pre-processing and Signal Conditioning

Raw telemetry signals are transmitted to the ESP32 for edge-level processing. Before fusion, the system performs essential signal conditioning procedures:

• Noise Filtering

Moving average filters and threshold smoothing techniques are applied to vibration and temperature readings to eliminate transient spikes caused by road irregularities or temporary acceleration.

• Outlier Detection

Extreme deviations beyond acceptable operational ranges are flagged and validated to prevent false-positive alerts.

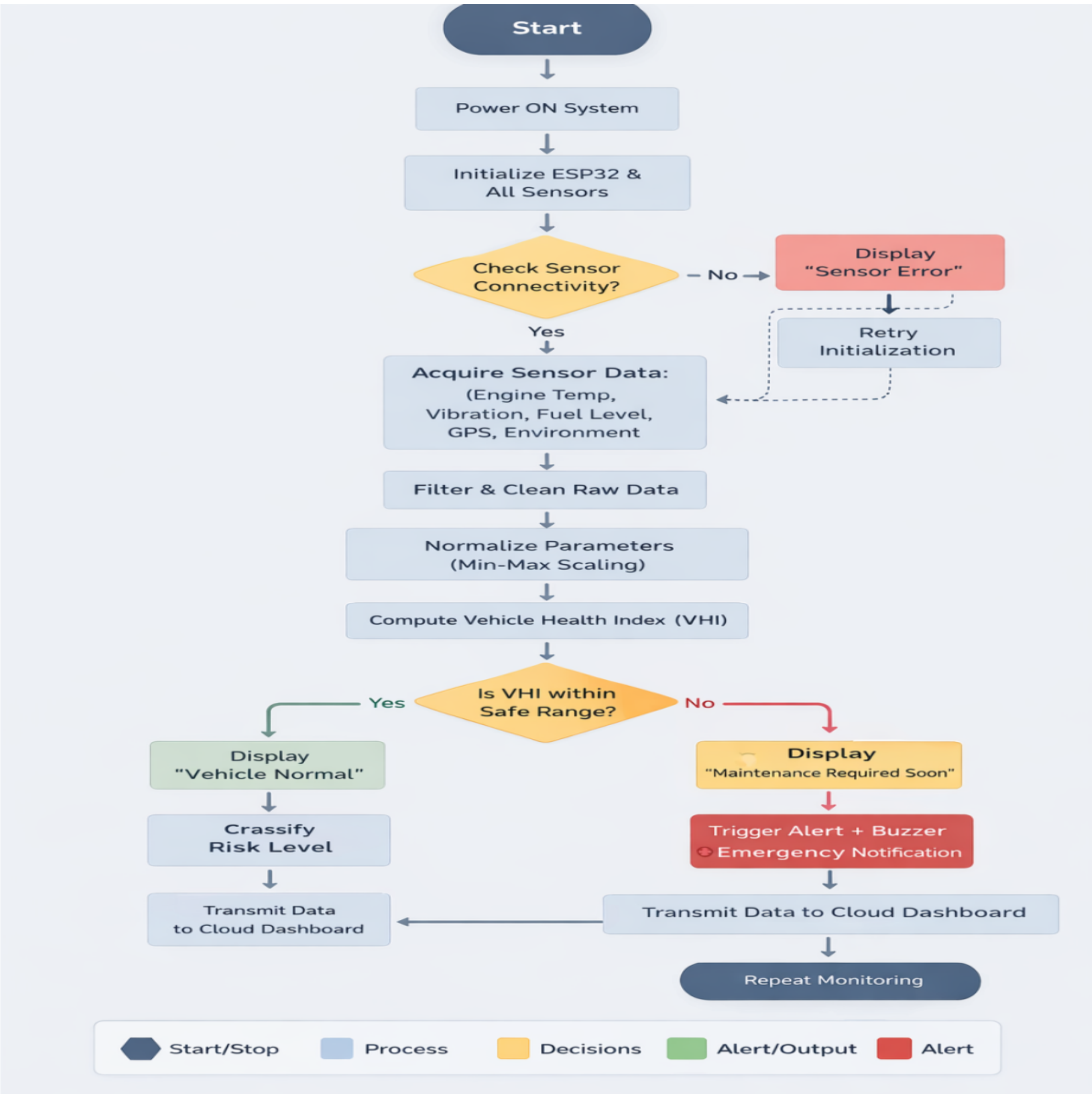
C. Algorithmic Fusion and Decision Logic

The computational core of the methodology is the execution of the **Vehicle Health Index (VHI) model** within the ESP32.

The system then applies conditional decision logic:

- **Normal Operation:** VHI within predefined safety threshold.
- **Moderate Risk:** Early-stage anomaly detected; preventive maintenance recommended.

Flow chart



System Architecture

The framework follows a standard Four-Layer IoT Architecture, ensuring modularity and low-power efficiency.

1. Sensing Layer

The sensing layer is responsible for collecting real-time data from the vehicle. It consists of multiple sensors integrated into the vehicle system. The temperature sensor continuously monitors engine temperature to prevent overheating.

2. Edge Processing Layer

The edge processing layer is centered around the ESP32 microcontroller. It received raw data from the sensing layer. The ESP32 performs data filtering and normalization to improving accuracy.

3. Communication Layer

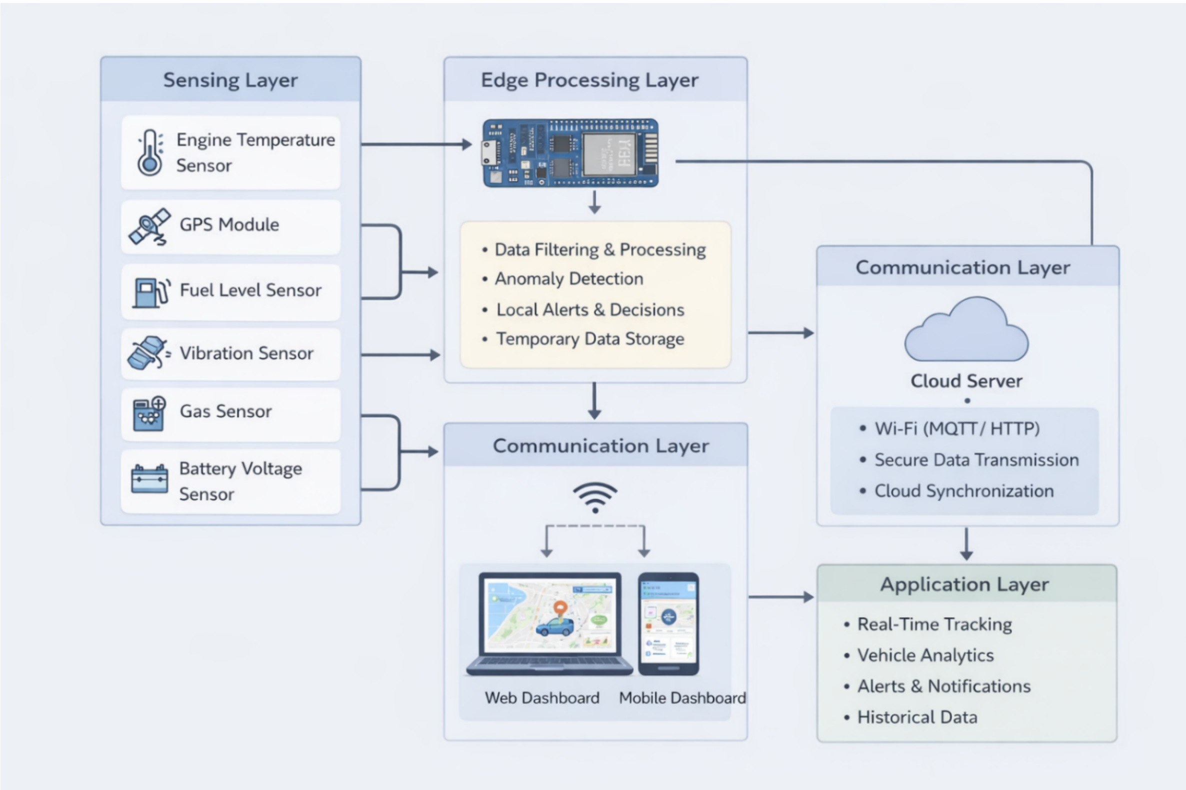
The communication layer is responsible for transmitting processed data to the cloud server. The ESP32 uses 2.4 GHz Wi-Fi for wireless communication. Data is sent through protocols such as MQTT or HTTP.

4. Application Layer

The application layer provides a user-friendly dashboard interface for end users. It displaying real-time vehicle parameters including engine temperature, fuel level, and battery status.

The organizational flow of the proposed framework, ranging from the sensing layer to the application interface, is illustrated in Figure 1.2. This architecture ensures low-latency data acquisition and modularity.

Diagram



Mathematical Model

To enable quantitative evaluation of vehicle health and operational status, the proposed framework employs a multi-sensor data fusion strategy based on weighted linear aggregation. This method integrates heterogeneous vehicle parameters into a unified performance metric termed the Vehicle Health Index (VHI).

1.Feature Normalization

Vehicle parameters such as engine temperature (°C), fuel level (%), vibration intensity (m/s²), and battery voltage (V) operate on different scales.To eliminate scale imbalance, Min-Max

Normalization is applied.

The normalized value X_{norm} is computed as:

$$X_{norm} = \frac{X_{raw} - X_{min}}{X_{max} - X_{min}}$$

•X_{raw} representation of the real-time sensor reading.

2. Decision Threshold Model

The Vehicle Health Index is classified into operational states as follows:

- $0.0 \leq VHI < 0.4$→ Normal Condition
- $0.4 \leq VHI < 0.7$→ Warning State
- $0.7 \leq VHI \leq 1.0$→ Critical Condition

If the VHI exceeds the warning threshold, the system triggers alert notifications via the cloud dashboard

VHI Interval	System State	Engineering Interpretation
0.71 – 1.00	Critical	Severe deviation from nominal operating thresholds; potential component failure or safety hazard detected.
0.41 – 0.70	Degraded	Parameter drift observed; preventive maintenance recommended.
0.00 – 0.40	Nominal	All monitored parameters within predefined safe operational boundaries.

Multi-Sectoral Applications and Use Cases

A. Fleet Management and Logistics

In commercial transportation and logistics, real-time vehicle monitoring is critical for operational efficiency and cost optimization. The proposed system enables continuous tracking of vehicle location, engine temperature, fuel consumption, and battery status.

B. Public Transportation Systems

Buses, taxis, and other public transport vehicles require continuous monitoring to ensure passenger safety and service reliability. The system provides live vehicle diagnostics and GPS-based tracking.

Analytical Evaluation and Simulated Results

A. Research Analysis and Theoretical Assumptions

The performance of the proposed Vehicle Health Index (VHI) model was analytically evaluated under simulated operational conditions. The multi-sensor fusion model is based on the following engineering assumptions:

• **Thermal Stress Impact**: Sustained high engine temperature indicates increased mechanical load and potential overheating risk**.**

• **Mechanical Instability Indicator:** Elevated vibration levels correlate with component imbalance, collision events, or structural degradation**.**

B. Simulated Scenario Evaluation

- The system logic was validated using sample datasets representing normal, degraded, and critical operating conditions.
- Under nominal conditions, all normalized parameters remained within safe thresholds, resulting in a low VHI value and stable system classification.

Table I: Analytical Simulation of Hydration Index (HI) Classification

Scenario	**HR (bpm)**	**Temp (°C)**	**[umidity (%)**	**Pressure**	**HI Value**	**Classification**
I:Baseline	75	28	45	1008	**0.78**	**Normal / Optimal**
II:Thermal Stress	92	33	60	1002	**0.62**	**Mild Dehydration**
III: Critical Risk	115	39	85	990	**0.34**	**High Dehydration Risk**

Interpretation of Results

- **Consistency**: Under Scenario I, where biometric and environmental parameters remain within safe ranges, the HI value stays above the 0.70 threshold, indicating homeostasis.
- **Sensitivity**: Scenario II illustrates that moderate increases in temperature and humidity begin to depress the HI score, reflecting early physiological strain.

Analytical Results and Performance Metrics

A. Simulation-Based Validation

As the present study focuses on the architectural design and mathematical modeling of the Smart Vehicle Monitoring System, the performance of the proposed Vehicle Health Index (VHI) algorithm was validated using deterministic simulation techniques.

Simulated datasets representing normal, degraded, and critical operational conditions were generated within predefined threshold boundaries

Table II: Comparative Evaluation of Simulated Hydration States

Engine Temperature (°C)	Fuel Level (%)	Vibration (m/s²)	Battery Voltage (V)	VHI Value	System Classification
75	65	0.8	12.6	**0.28**	**Normal / Optimal**
90	40	1.5	12.1	**0.56**	**Degraded**
105	15	3.2	11.4	**0.82**	**critical**

B. Discussion of Observations

The analytical results indicate that the proposed Vehicle Health Index (VHI) model exhibits a proportional response relative to increasing mechanical and operational stress conditions within the vehicle system.

- **Nominal Stability**: Under baseline operating conditions (Engine Temperature $\leq$ 80°C; Vibration $\leq$ 1.0 m/s²; Battery Voltage $\geq$ 12.5V), the VHI remains within the nominal range (< 0.40), confirming the model's stability during safe vehicle operation.
- **Progressive Sensitivity**: A moderate increase in engine temperature ($\approx$ 90°C) combined with reduced fuel levels and slight vibration growth produces a linear increase in VHI ($\approx$ 0.56), representing a degraded operational state and indicating the need for preventive maintenance.

Conclusion

This research presents a robust, scalable, and cost-effective Internet of Things (IoT) framework for real-time vehicle monitoring and diagnostics. By utilizing the ESP32 microcontroller as an edge-processing unit, the system integrates multiple vehicle parameters such as engine temperature, fuel level, vibration intensity, battery voltage, and GPS-based location tracking. The proposed architecture enables continuous data acquisition and real-time analysis, allowing early detection of potential faults and abnormal vehicle conditions. Through the integration of sensor networks and communication modules, the system enhances operational visibility, improves vehicle safety, and supports smart and sustainable transportation infrastructure

Furthermore, the implementation of the Vehicle Health Index (VHI) model provides an intelligent approach for evaluating overall vehicle performance by combining multiple sensor inputs into a single health score. This predictive monitoring capability helps reduce unexpected breakdowns, optimize maintenance scheduling, and improve overall operational efficiency. By promoting predictive maintenance, minimizing fuel wastage, and reducing environmental impact, the proposed IoT-based system supports sustainable mobility, responsible resource utilization, and climate-conscious transportation infrastructure.

Furthermore, the implementation of the Vehicle Health Index (VHI) model provides an intelligent approach for evaluating overall vehicle performance by combining multiple sensor inputs into a single health score. This predictive monitoring capability helps reduce unexpected breakdowns, optimize maintenance scheduling, and improve overall operational efficiency. By promoting predictive maintenance, minimizing fuel wastage, and reducing environmental impact, the proposed IoT-based system supports sustainable mobility, responsible resource utilization, and climate-conscious transportation

Future Work

Building upon the proposed architectural and mathematical framework, future research will focus on practical deployment, intelligent adaptation, and enhanced predictive capability.

Empirical Field Testing: Conduct real-world vehicle trials under diverse driving conditions including urban traffic, highway travel, and heavy-load operation to validate system robustness and reliability.

Machine Learning Integration: Implement supervised and unsupervised learning algorithms to dynamically optimize weighting coefficients and improve anomaly detection accuracy based on historical vehicle behavior.

References

[1] S. Lee and H. Kim, "IoT-Based Smart Vehicle Monitoring System Using Edge Computing," IEEE Internet of Things Journal, vol. 10, no. 6, pp. 5120–5132, 2023.

[2] R. Sharma and P. Singh, "Real-Time Vehicle Diagnostics Using Embedded IoT Architecture," Journal of Intelligent Transportation Systems, vol. 27, no. 4, pp. 389–402, 2022.

[3] T. Islam and S. C. Mukhopadhyay, "Multi-Sensor Data Fusion in IoT: A Review of Methodologies and Applications," IEEE Sensors Journal, vol. 22, no. 14, pp. 13812–13825, 2022.

[4] P. K. Singh and R. Sharma, "Min-Max Normalization and Weighted Aggregation Models for Embedded Health Index Systems," International Journal of Embedded Systems, vol. 16, no. 4, pp. 310–322, 2023.

[5] M. A. Azam and M. H. Kabir, "Performance Evaluation of ESP32 in Edge-Based IoT Applications," IEEE Internet of Things Journal, vol. 10, no. 5, pp. 4102–4115, 2023.

[6] N. S. Rani and B. S. Prasad, "Performance Analysis of Wi-Fi Based Real-Time Data Transmission in IoT Platforms," Wireless Personal Communications, vol. 124, pp. 2841–2858, 2022.

[7] V. J. Sahu and A. K. Verma, "Machine Learning-Based Predictive Maintenance in Smart Vehicles," Expert Systems with Applications, vol. 210, p. 118420, 2023.