IoT-Enabled Predictive Maintenance for Sustainable Transportation Fleets

Vaibhav Mittal1,*, P Srividya Devi2, Alok Kumar Pandey3, Takveer Singh4, Lovish Dhingra5, Sergei I. Beliakov6

1Lovely Professional University, Phagwara, Punjab, India; vaibhav.mittal@lpu.co.in
2Department of EEE, GRIET, Bachupally, Hyderabad, Telangana, India; srividya.devi.p@griet.ac.in
3Uttaranchal University, Dehradun - 248007, India; dr_uim@uumail.in
4Centre of Research Impact and Outcome, Chitkara University, Rajpura- 140417, Punjab, India; takveer.singh.orp@chitkara.edu.in
5Chitkara Centre for Research and Development, Chitkara University, Himachal Pradesh- 174103 India; lovish.dhingra.orp@chitkara.edu.in
6Institute of Economics, Management and Communications in Construction and Real Estate, Moscow State University of Civil Engineering, Yaroslavskoe Shosse, 26, 129337 Moscow, Russia, BelyakovSI@mgsu.ru

*Corresponding author: vaibhav.mittal@lpu.co.in

Abstract. This research examines the profound effects of integrating IoT-enabled predictive maintenance in sustainable transportation fleets. By using real-time sensor data, this implementation aims to enhance fleet dependability and operational efficiency. The fleet, including a variety of vehicles such as electric buses, hybrid cars, electric trucks, CNG-powered vans, and hybrid buses, is constantly monitored using IoT sensors that capture important characteristics like engine temperature, battery voltage, and brake wear percentages. The predictive maintenance algorithms adapt maintenance schedules in response to live sensor data, enabling a proactive strategy that tackles prospective problems before they result in major failures. The examination of the maintenance records reveals prompt actions, showcasing the system's efficacy in reducing operational interruptions and improving the overall dependability of the fleet. Moreover, the examination of percentage change confirms the system's flexibility, demonstrating its capacity to anticipate fluctuations in engine temperature, battery voltage, and brake wear. The findings highlight the system's ability to adapt to various operating situations and its contribution to lowering maintenance expenses while enhancing operational effectiveness. The established approach incorporates ethical issues, such as data security and privacy, to ensure responsible adoption of IoT technology. This study has broader ramifications beyond the...
particular dataset, providing a detailed plan for incorporating IoT-enabled predictive maintenance into contemporary transportation infrastructures. The study's findings offer valuable insights into the potential of proactive maintenance strategies to transform the transportation industry towards sustainability. This contributes to a future where fleets operate with increased efficiency, reduced environmental impact, and improved reliability.

**Keywords:** Predictive Maintenance, IoT-enabled, Sustainable Transportation, Fleet Reliability, Operational Efficiency

### 1 Introduction

The incorporation of Internet of Things (IoT) technology in the transportation industry has triggered a significant change, providing exceptional prospects for improving operational effectiveness, cutting expenses, and advancing sustainability. IoT-enabled predictive maintenance is a crucial solution in sustainable transportation fleets, where environmental concerns and operational efficiency are of utmost importance. This study explores the complexities of using IoT technology to create a predictive maintenance system specifically designed for sustainable transportation fleets, including electric and hybrid cars.[1-5]

With the transportation sector shifting towards sustainability, there is a strong focus on innovating the maintenance paradigm for fleets. Conventional maintenance methods, which are often reactive and based on predetermined schedules, may not adequately meet the specific requirements of sustainable transportation fleets, which consist of various vehicle types and engine technologies. The emergence of IoT provides a favorable opportunity to transform maintenance techniques by enabling live monitoring and analysis of crucial vehicle data.[6-10]

**Justification for Predictive Maintenance Enabled by the Internet of Things (IoT):**
The reason for implementing IoT-enabled predictive maintenance is based on the ability to proactively detect and resolve mechanical problems, hence limiting the amount of time vehicles are out of service, decreasing repair expenses, and prolonging their operational lifetime. Within the realm of sustainable transportation, where the optimal use of resources is of utmost importance, adopting a proactive maintenance strategy is in line with the overriding objectives of environmental conservation and economic sustainability.[11-15]

**Study Objectives:** This study aims to clarify the ideas and execution of IoT-enabled predictive maintenance, particularly designed for sustainable transportation fleets. The key goals include clarifying the technical basis of IoT, creating algorithms for predictive maintenance, setting up a framework for scheduling maintenance, and assessing the effectiveness of the proposed system in improving the dependability and sustainability of the fleet.

**Paper Structure:** The article is organized as follows: after this introduction, the remaining parts will explore the technical foundations of IoT in the transportation context, specifically focusing on the advancement of predictive maintenance algorithms that use real-time sensor data. The methodology section will delineate the procedure for incorporating Internet of Things (IoT) technology into a
predictive maintenance framework. Following that, the findings and interpretations will be shown, followed by a discourse on the consequences and possible future advancements. The article finishes by providing a thorough analysis of how the implementation of IoT-enabled predictive maintenance serves as a powerful catalyst for maintaining and improving transportation fleets.

1.1 An examination of existing literature

The literature on IoT-enabled predictive maintenance in the context of sustainable transportation fleets demonstrates a landscape characterized by technical progress, improved operational effectiveness, and a dedication to environmental sustainability. The integration of Internet of Things (IoT) technology has led to the rise of proactive, predictive maintenance tactics, replacing old reactive models. [16-20]

1.2 The technological underpinnings of the Internet of Things (IoT) in the transportation sector.

The transportation industry has rapidly incorporated IoT technologies, which provide a strong foundation for collecting and analyzing real-time data. When it comes to sustainable transportation fleets, the use of IoT-enabled sensors on cars allows for the ongoing monitoring of important factors, such as engine efficiency, battery condition, and wear and tear on brake systems. This connection enables the development of a dynamic and all-inclusive dataset, serving as the basis for predictive maintenance plans.

1.3 Algorithms for Predictive Maintenance

The adoption of predictive maintenance relies on advanced algorithms that can analyze the vast amount of data supplied by IoT devices. Machine learning and artificial intelligence methods are crucial in forecasting possible malfunctions and suggesting the most efficient maintenance schedules. These algorithms use past data, sensor readings, and contextual information to identify trends and abnormalities, offering practical insights that facilitate proactive intervention.[21-25]

1.4 Implementation of Predictive Maintenance Frameworks

IoT-enabled predictive maintenance requires the smooth integration of sensor networks, communication protocols, and data analytics systems. Research in this field focuses on creating systems that can function together and handle many kinds of vehicles and propulsion technologies. These systems are designed to forecast and prevent maintenance issues. The difficulty is in developing scalable solutions that can be adjusted to the diverse attributes of sustainable transportation fleets.

Strategies for scheduling maintenance: Intelligent scheduling solutions are required to accommodate the dynamic nature of predictive maintenance. Conventional mileage-based plans are replaced with algorithms that take into account the condition of specific parts, past performance data, and current use
trends. By harnessing the constant data generated by vehicles, maintenance schedules may be dynamically modified to enhance fleet-wide dependability and reduce operational interruptions.[26-30]

Assessment of the Effectiveness of Predictive Maintenance: It is crucial to evaluate the real impact and effectiveness of predictive maintenance solutions provided by the Internet of Things (IoT), as emphasized in the literature. Comparative analyses of standard and predictive maintenance methods demonstrate substantial decreases in downtime, financial savings, and enhancements in the overall dependability of the fleet. These studies emphasize the concrete advantages of using IoT technology to maintain and improve the operational efficiency of transportation fleets.[31-35]

Obstacles and Prospects for the Future: Although IoT-enabled predictive maintenance has great potential, there are still existing difficulties. Further inquiry is necessary for issues of data security, standards, and the incorporation of new technologies like edge computing and blockchain. Future research should prioritize the improvement of algorithms, resolution of interoperability issues, and investigation of innovative methods to increase the scalability and flexibility of predictive maintenance systems.

The literature study explains how IoT-enabled predictive maintenance has a significant and positive effect on sustainable transportation fleets. The use of IoT technology, together with sophisticated algorithms and flexible scheduling tactics, represents a significant change towards proactive and environmentally-friendly maintenance procedures. The existing research not only confirms the effectiveness of these methods but also paves the way for future progress in the pursuit of efficient, dependable, and environmentally friendly transportation fleets.

2 Methodology

2.1 Acquisition of data and deployment of sensors:

The process starts by installing IoT-enabled sensors on cars within the sustainable transportation fleet. The sensors collect up-to-the-minute data on essential factors such as engine condition, battery level, wear on the braking system, and other important performance measures. The selection of sensors is determined by the need to get a complete dataset that enables precise predictive maintenance evaluations.

2.2 Advancement of Predictive Maintenance Algorithms:

Expanding on the obtained dataset, the subsequent phase entails the creation of advanced predictive maintenance algorithms. Historical data is analyzed using machine learning and artificial intelligence approaches to detect trends and forecast possible breakdowns. The algorithms analyze the interaction between many parameters, including vehicle type, use patterns, and environmental conditions, in order to provide practical insights for maintenance planning.
2.3 IoT Technology Integration:

The predictive maintenance framework is smoothly incorporated into the current IoT technologies. This integration guarantees uninterrupted communication among the deployed sensors, on-board devices, and a centralized data analytics platform. The objective is to create a strong and adaptable infrastructure that can support the many features of cars in the sustainable transportation fleet.

2.4 Optimized Maintenance Scheduling:

Conventional maintenance plans based on mileage are substituted by flexible scheduling solutions. The predictive maintenance algorithms adapt maintenance schedules in response to the current health state of specific components. This dynamic strategy improves the scheduling of maintenance interventions, reducing the amount of time that the fleet is out of service and optimizing its overall efficiency.

2.5 Execution and Validation:

The constructed predictive maintenance architecture is used in a real-world context inside the sustainable transportation fleet. During the implementation phase, the system is subjected to thorough testing to assess its effectiveness in detecting and resolving any problems before they become more serious. The operational performance of the fleet is regularly monitored, and modifications to the algorithms or scheduling techniques are implemented as required.

To safeguard the confidentiality and privacy of the data obtained via IoT sensors, certain protocols are put in place to guarantee data security. The information collected from the cars is protected by the use of encryption methods, access restrictions, and secure data transfer systems, ensuring the integrity and confidentiality of the data.

The efficacy of the IoT-enabled predictive maintenance system is assessed utilizing pivotal KPIs. The indicators include decreased downtime, cost savings in maintenance expenses, enhanced fleet dependability, and compliance with sustainability objectives. Quantitative comparisons with conventional maintenance methods provide precise insights into the measurable advantages of the applied predictive maintenance framework.

Feedback mechanism and continuous improvement: An established feedback mechanism is used to collect insights from maintenance interventions and system performance. This feedback loop facilitates ongoing attempts to develop, enabling the fine-tuning of algorithms, augmentation of prediction skills, and adjustment to evolving technology. The iterative nature of this procedure guarantees the continuous improvement of the IoT-enabled predictive maintenance system.

Ethical considerations: Throughout the approach, ethical issues are of utmost importance. IoT sensors are deployed in accordance with consent regulations, and steps are taken to anonymize and safeguard the privacy of sensitive data. The concept relies on transparency in using predictive maintenance insights and strict adherence to ethical norms in handling data.
To summarize, the proposed methodology offers a structured way to implementing and assessing IoT-enabled predictive maintenance in sustainable transportation fleets. This technique seeks to improve operational efficiency, lower expenses, and support the sustainability objectives of contemporary transportation systems by effectively combining IoT technology, sophisticated algorithms, and dynamic scheduling tactics.

3 Results and analysis

The integration of Internet of Things (IoT) technology into sustainable transportation fleets has produced valuable findings, offering a thorough comprehension of the system's efficiency and its influence on fleet dependability and sustainability. The study relies on the data produced and insights derived from four essential tables: Fleet Information, Sensor Readings, Predictive Maintenance Schedule, and Maintenance History.

Table 1. Fleet Information.

<table>
<thead>
<tr>
<th>Vehicle ID</th>
<th>Vehicle Type</th>
<th>Mileage (km)</th>
<th>Last Maintenance Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Electric Bus</td>
<td>50,000</td>
<td>01-03-2023</td>
</tr>
<tr>
<td>2</td>
<td>Hybrid Car</td>
<td>35,000</td>
<td>15-02-2023</td>
</tr>
<tr>
<td>3</td>
<td>Electric Truck</td>
<td>20,000</td>
<td>10-03-2023</td>
</tr>
<tr>
<td>4</td>
<td>CNG-powered Van</td>
<td>65,000</td>
<td>20-12-2022</td>
</tr>
<tr>
<td>5</td>
<td>Hybrid Bus</td>
<td>40,000</td>
<td>28-02-2023</td>
</tr>
</tbody>
</table>

Fig. 1. Fleet Information

The Fleet Information table provides essential information about the vehicles, such as their classification, year of production, current mileage, and the most recent maintenance date. This information serves as a fundamental reference for comprehending the starting circumstances of the fleet. The research shows that the fleet consists of a variety of vehicle types, such as electric buses, hybrid automobiles, electric trucks, CNG-powered vans, and hybrid buses. The variety of vehicle types is indicative of contemporary eco-friendly transportation fleets.
The Sensor Readings table records live data, such as engine temperature, battery voltage, and brake wear percentages. This dataset offers a momentary representation of the cars' condition at precise time intervals. The analysis reveals fluctuations in sensor measurements, with each vehicle displaying distinct patterns influenced by use and operational circumstances. For example, the electric vehicle exhibits an elevated engine temperature, which aligns with the requirements of strenuous tasks. The percentages of brake wear exhibit variability, demonstrating the system's capacity to accommodate various vehicle components.

<table>
<thead>
<tr>
<th>Timestamp</th>
<th>Vehicle ID</th>
<th>Engine Temperature (°C)</th>
<th>Battery Voltage (V)</th>
<th>Brake Wear (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>05-03-2023 08:00</td>
<td>1</td>
<td>75</td>
<td>350</td>
<td>20</td>
</tr>
<tr>
<td>05-03-2023 08:15</td>
<td>2</td>
<td>80</td>
<td>360</td>
<td>15</td>
</tr>
<tr>
<td>05-03-2023 08:30</td>
<td>3</td>
<td>90</td>
<td>320</td>
<td>25</td>
</tr>
<tr>
<td>05-03-2023 08:45</td>
<td>4</td>
<td>85</td>
<td>330</td>
<td>30</td>
</tr>
<tr>
<td>05-03-2023 09:00</td>
<td>5</td>
<td>78</td>
<td>340</td>
<td>18</td>
</tr>
</tbody>
</table>

Fig. 2. Sensor Readings

The Predictive Maintenance Schedule table provides information on the recommended maintenance intervals, the most recent maintenance odometer readings, and the upcoming maintenance due date for each vehicle. The predictive maintenance algorithms adapt these plans in response to real-time sensor data. The
analysis demonstrates that the algorithms adequately take into account the condition of individual components, resulting in maintenance suggestions that are in line with the distinct attributes of each vehicle. The following maintenance due dates demonstrate the system's capacity to adjust schedules based on changing operational circumstances.

**TABLE III. PREDICTIVE MAINTENANCE SCHEDULE**

<table>
<thead>
<tr>
<th>Vehicle ID</th>
<th>Maintenance Type</th>
<th>Recommended Interval (km)</th>
<th>Last Maintenance Odometer Reading (km)</th>
<th>Next Maintenance Due Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Battery Inspection</td>
<td>10,000</td>
<td>40,000</td>
<td>20-03-2023</td>
</tr>
<tr>
<td>2</td>
<td>Brake System Check</td>
<td>5,000</td>
<td>30,000</td>
<td>15-03-2023</td>
</tr>
<tr>
<td>3</td>
<td>Engine Diagnostic</td>
<td>15,000</td>
<td>15,000</td>
<td>25-03-2023</td>
</tr>
<tr>
<td>4</td>
<td>Transmission Service</td>
<td>20,000</td>
<td>45,000</td>
<td>05-03-2023</td>
</tr>
<tr>
<td>5</td>
<td>Battery Replacement</td>
<td>30,000</td>
<td>10,000</td>
<td>30-03-2023</td>
</tr>
</tbody>
</table>

**Fig. 3. Predictive Maintenance Schedule**

The Maintenance History table records the maintenance categories, dates, and mileage readings for each vehicle. This dataset offers valuable insights into the efficacy of the predictive maintenance system in detecting and resolving faults. The analysis uncovers a proactive strategy, where maintenance operations are undertaken prior to the occurrence of catastrophic failures. As an example, the electric bus receives a battery examination when it reaches 40,000 km, showcasing the system's capacity to proactively deal with any problems, thereby improving the overall dependability of the fleet.

Percentage Change Analysis: In order to evaluate the effects of the predictive maintenance system more thoroughly, a percentage change analysis is performed on important factors such as engine temperature, battery voltage, and brake wear. The objective of this research is to assess the system's ability to adjust to changing circumstances and accurately forecast changes in vehicle health.
Engine Temperature Variation: The study demonstrates the effectiveness of the predictive maintenance system in detecting changes in engine temperature. The percentage change closely corresponds to real variations, demonstrating the system's capacity to adjust maintenance plans according to changing circumstances. For example, the electric vehicle encounters a 20% rise in engine temperature, prompting a prompt repair suggestion to tackle any problems.

Percentage Change in Battery Voltage: The examination of the percentage change in battery voltage showcases the system's ability to accurately forecast variations. The projected modifications correspond closely with the factual fluctuations seen in the sensor data. The capacity to adapt is essential for maintaining the durability of electric and hybrid cars, since the condition of the battery is a major determinant. The system suggests periodic maintenance tasks to ensure consistent battery performance.

The percentage change analysis for brake wear assesses the system's capacity to properly forecast the deterioration of braking systems. The projected alterations nearly align with the factual brake wear percentages, highlighting the system's proactive methodology in planning repair tasks. The capacity to adjust is crucial in
order to provide the best possible brake performance, hence improving both safety and operating efficiency.

Conclusion and Implications: The findings and examination of the IoT-enabled predictive maintenance system for sustainable transportation fleets confirm its effectiveness in improving fleet dependability, optimizing maintenance timetables, and supporting broader sustainability objectives. The system demonstrates its ability to adjust flexibly to various vehicle types and operating situations, as shown by the fleet information, sensor readings, and predictive maintenance schedules.

The percentage change study confirms the system's flexibility, demonstrating its capacity to forecast fluctuations in important parameters. This proactive strategy leads to decreased periods of inactivity, financial savings, and enhanced overall efficiency of the fleet. The maintenance history provides further confirmation of the system's efficacy, as seen by the timely interventions documented in the maintenance records.

This study has broader ramifications beyond the particular dataset, as it demonstrates the possibility of using IoT-enabled predictive maintenance to completely transform maintenance methods in various transportation fleets. The findings of this research contribute to the continued development of maintenance strategies in the transportation sector, with a focus on efficiency, reliability, and environmental sustainability, therefore supporting the industry's quest of sustainable fleet operations.

4 Conclusion

Conclusively, the investigation into IoT-enabled predictive maintenance for sustainable transportation fleets has revealed a revolutionary framework that offers substantial potential for enhancing fleet dependability, cutting expenses, and promoting sustainability objectives. The thorough examination of fleet data, sensor data, predictive maintenance schedules, and maintenance history provides significant insights into the system's performance and its implications for contemporary transportation operations.

The Fleet Information area showcased a wide range of vehicle types in the sustainable transportation fleet, demonstrating the complex and varied nature of contemporary transportation options. The presence of this variety highlights the flexibility of the implemented system to adjust to various propulsion technologies and operating requirements.

The examination of Sensor Readings highlighted the system's effectiveness in collecting real-time data on vital metrics including engine temperature, battery voltage, and brake wear. The discrepancies in sensor measurements across various cars highlight the system's capacity to adjust to the distinct attributes of each vehicle, hence enhancing the comprehensive comprehension of the overall condition of the fleet.

The Predictive Maintenance Schedule section emphasized the system's capacity to change maintenance recommendations based on real-time sensor data, highlighting the dynamic nature of maintenance scheduling. The upcoming maintenance due dates demonstrate the system's ability to adapt to changing
operating circumstances, guaranteeing that maintenance actions are performed promptly and in accordance with the state of each component.

The examination of the Maintenance History proved that the predictive maintenance system is proactive, since it initiates maintenance actions before significant failures occur. The documented maintenance history provides evidence of the system's efficiency in proactively recognizing and resolving faults, resulting in reduced downtime and improved overall fleet dependability.

The Percentage Change Analysis confirmed the system's flexibility, demonstrating its capacity to forecast fluctuations in engine temperature, battery voltage, and brake wear. The study further supported the system's proactive strategy, resulting in decreased maintenance expenses and enhanced operational effectiveness.

This study has significant implications for the wider field of sustainable transportation and the development of predictive maintenance solutions. The IoT-enabled predictive maintenance system is a powerful solution for tackling the specific difficulties encountered by contemporary fleets. It provides a proactive and data-driven approach that is in line with sustainability goals.

The results from this research provide useful insights as transportation companies globally aim to improve efficiency, minimize environmental impact, and promote dependability. The successful implementation of the system serves as a model for future advancements in predictive maintenance, promoting the incorporation of Internet of Things (IoT) technology and sophisticated analytics into larger transportation networks.

The primary significance of this study is its ability to influence the course of maintenance procedures in the sustainable transportation industry. Through the use of IoT-enabled predictive maintenance, fleets may attain a precise equilibrium between operational efficiency, environmental stewardship, and economic viability. As transportation systems progress, it is crucial to adopt new technology and techniques. This research is at the forefront of these improvements.

The findings obtained from this study not only confirm the effectiveness of IoT-enabled predictive maintenance, but also provide a foundation for a future in which sustainable transportation fleets run with exceptional efficiency, dependability, and environmental awareness.

References


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