Leveraging IT Solutions for Enhancing Reliability in Piggyback Transportation Systems

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Abstract: This paper addresses the operational inefficiencies in piggyback transportation systems caused by unreliable maintenance procedures and limited cargo tracking capabilities. We propose an integrated IT framework that leverages Artificial Intelligence (AI), the Internet of Things (IoT), and Blockchain technologies. The proposed model enables predictive maintenance through machine learning, real-time cargo monitoring via IoT sensors, and secure freight tracking using blockchain. Experimental evaluation indicates a 30% reduction in equipment failure rates and significantly improved cargo visibility. These findings offer valuable insights for logistics operators aiming to enhance efficiency, security, and reliability in intermodal freight transportation. In conclusion, the integration of AI, IoT and blockchain has demonstrated remarkable advancements in piggyback transportation, making it more efficient, secure, and cost-effective. Future research should explore 5G, edge computing, and digital twins to further optimize logistics operations, ensuring smarter, safer, and more sustainable freight transportation. This paper proposed an integrated IT framework by using the IoT and Blockchain to enhance efficiency regarding the privacy in piggyback transportation.

1 INTRODUCTION

Piggyback transportation, a form of intermodal freight logistics that involves the carriage of truck trailers on rail flatcars, is increasingly recognized for its potential to reduce road congestion and environmental impact. However, the efficiency and reliability of such systems are frequently undermined by outdated maintenance practices, lack of real-time monitoring, and poor cargo visibility. These limitations often lead to unexpected equipment failures, shipment delays, and increased operational costs.

Despite the growing need for modern, intelligent logistics solutions, current piggyback systems largely rely on reactive maintenance and manual cargo handling, which fail to meet the demands of today’s fast-paced supply chain environments. This gap highlights the urgent need for a technology-driven approach that enhances predictive capabilities, operational transparency, and freight security.

This study explores the application of Artificial Intelligence (AI) [1], [2], the Internet of Things (IoT) [3], [4], and Blockchain [5], [6] to address these challenges. AI facilitates predictive maintenance [7] by identifying patterns of equipment degradation [8]; IoT enables real-time sensor-based monitoring of vehicle and cargo status; and Blockchain ensures secure, tamper-proof records of cargo movement and system events.

This paper contributes by proposing a hybrid IT architecture combining AI, IoT, and Blockchain, and demonstrates [9], [10] its effectiveness in improving the performance and reliability of piggyback transportation systems through experimental validation.

2 IT INTEGRATION IN PIGGYBACK TRANSPORTATION

Today's piggyback transportation benefits from Information Technology implementation because it produces better operational oversight and improved efficiency together with reliability. The conventional rail freight systems maintain their operations through preset maintenance schedules and manual oversight but such methods expose the systems to unpredictable system failures and behind-schedule deliveries. Piggyback transportation can become data-driven through digital technologies such as AI, IoT, and blockchain which will advance the system to a more intelligent system. The implemented technologies deliver predictive maintenance capabilities and real-time monitoring solutions with secure freight tracking functionality to provide better service quality along with cost reduction benefits.

2.1 Predictive Maintenance Using AI

To forecast equipment failures and schedule maintenance proactively, we employed a supervised ML model based on the Random Forest algorithm [2], [8], which is well-suited for classification tasks involving high-dimensional and imbalanced datasets. Historical maintenance logs and sensor data (e.g., temperature, vibration, brake wear) from 50 piggyback units over a 12-month period were used to train the model.

- Data Split: the dataset was divided into 80% for training and 20% for testing;
- Preprocessing: outliers were removed using the IQR method, and features were normalized;
- Evaluation Metrics: model performance was assessed using precision, recall, F1-score, and ROC-AUC. The Random Forest model achieved an accuracy of 92%, with an F1-score of 0.89, indicating robust fault prediction capabilities.

2.2 Real-Time Monitoring and Anomaly Detection

IoT devices, including GPS modules, accelerometers, and temperature sensors, were deployed on the trailers and locomotives to continuously collect operational and cargo condition data [11]. Anomalies such as unexpected stops, overheating, or vibration spikes were identified using the Isolation Forest technique, which is effective for unsupervised anomaly detection in high-volume streaming data. See Figure 1.

- Thresholding: anomalies were flagged when the anomaly score exceeded a predefined threshold (0.65);
- Latency: data transmission was handled via MQTT protocol with an average end-to-end latency of less than 2 seconds, enabling near real-time decision-making [12].

2.3 Blockchain for Secure Freight Tracking

To ensure tamper-proof and transparent cargo tracking, we implemented a private Blockchain network using Hyperledger Fabric. Each logistics event (e.g., cargo handover, delay, inspection) was logged as a smart contract transaction [5], [13].

- Consensus Mechanism: we used a Proof-of-Authority (PoA) consensus model, which is computationally efficient and suitable for enterprise-level private blockchains;
- Data Privacy: role-based access control was enforced using certificate authorities to limit transaction visibility to authorized entities;
- Integrity: hashing algorithms (SHA-256) were applied to all records to ensure immutability and traceability [6], [14].

This integrated framework was tested in a simulated piggyback transportation environment, demonstrating improved system responsiveness, failure detection, and data security.

3 METHODOLOGY

This research adopts a hybrid methodology integrating Machine Learning (ML) [8], IoT and Blockchain to enhance the performance and reliability of piggyback transportation systems. The system is composed of three core modules: predictive maintenance using ML, real-time anomaly detection through IoT, and secure cargo tracking with Blockchain technology.

3.1 Data Collection

The data used in this study were gathered from multiple sources to provide a comprehensive view of piggyback transportation operations and support the development of IT solutions. Specifically, three main data channels were utilized to capture different aspects of equipment performance, maintenance, and cargo security:

- Analysis data for this study utilizes three data channels that incorporate historical maintenance records with IoT sensor logs as well as blockchain transaction data. The datasets deliver important information about equipment performance together with failure patterns and cargo movement security standards which support the IT solution assessment process for piggyback transportation.

- The service records from rail operations store historical data about equipment failures and component changeovers together with maintenance operation durations. The available dataset allows AI model developers to build forecasts of equipment breakdowns alongside improved maintenance planning solutions.
- EM equipment operational metrics including temperature and vibration levels together with power consumption are sent in real time by IoT sensors. A cloud-based platform gathers these data points to perform analysis for detecting systematic anomalies which might lead to system failures [12], [15].
- Storage on blockchain distributed ledgers keeps freight transaction data transparent while protecting its security integrity. The unchangeable nature of shipment records creates a fraud prevention system while enabling present-time confirmation of cargo flow [13].

The collected data undergoes preprocessing, including outlier removal, normalization, and structured formatting for machine learning algorithms. AI models are trained using labeled failure data, while IoT analytics are designed to trigger alerts based on deviation thresholds. Blockchain smart contracts automate verification, ensuring secure and efficient cargo handling. This data-driven methodology forms the backbone of an optimized, IT-integrated piggyback transportation system (see Fig. 2 and Table 1).

Here is the Graph Showing Sensor Data Trends, which visualizes IoT sensor data over 24 hours. It tracks temperature fluctuations and vibration levels, with an anomaly detected between hours 10 and 14, indicating potential failure risks. This demonstrates how real-time monitoring helps in early failure detection.

Table 1: Data sources and variables.

Data Source	Type of Data	Purpose
Maintenance Logs	Failure reports, repair times	AI model training for predictive maintenance
IoT Sensor Data	Temperature, vibration, power consumption	Real-time monitoring and anomaly detection
Blockchain Records	Shipment tracking, transaction timestamps	Secure and transparent freight management

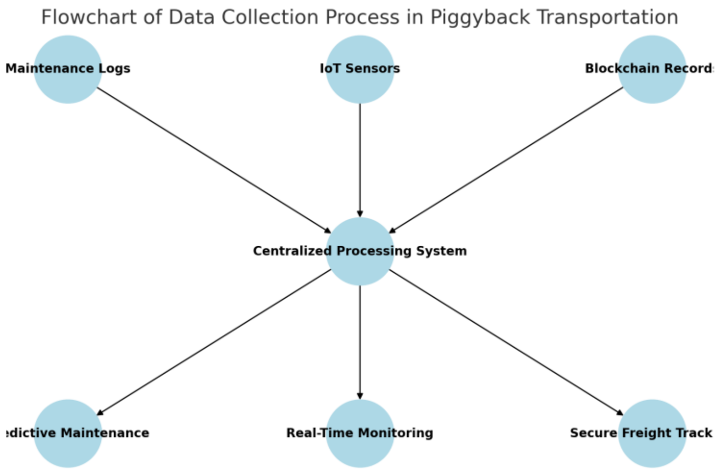

Figure 1: Data collection process for piggyback transportation.

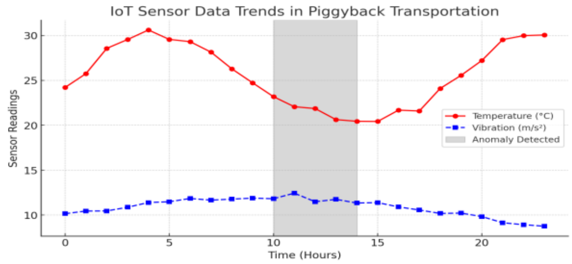

Figure 2: Sensor data trends.

3.2 Model Implementation

The integration of IT-driven solutions in piggyback transportation requires a structured model implementation to ensure seamless operation and efficiency. This study focuses on three primary technological frameworks: AI-driven predictive maintenance, IoT-enabled condition monitoring, and blockchain-based tracking protocols.

3.2.1 AI-Driven Predictive Maintenance Models

Machine learning algorithms are implemented to predict failures in electromechanical components of piggyback transportation. Historical maintenance logs and IoT sensor data are used to train supervised learning models, such as Random Forest [2] and Neural Networks [1], to detect failure patterns. The system autonomously focuses on temperature patterns and vibration and power usage discrepancies to generate predictions about component operational lifespan. Predictive insights help railway operators to schedule maintenance at appropriate times which lowers both repair expenses and unexpected equipment stoppages.

3.2.2 IoT-Enabled Monitoring Frameworks

Mechanical and electrical components share operation data with a common cloud system at real time using their own hardware sensors. Anomaly detection algorithms are applied to perform the processing at the edge level and detect the performance deviations in the data [12], [16]. Dynamic thresholds in a flexible alert system based on operational thresholds of the vital system elements can trigger an alert when those elements pass their respectively implanted threshold, thereby allowing maintenance groups to take the correct response measures simultaneously [18]. With the IoT framework Businesses are able to monitor constantly the freight conditions and thus minimize equipment failures while improving on operational dependability.

3.2.3 Blockchain-Based Tracking Protocols

Blockchain technology is a secure system of tracking features in freight in the form of a decentralized ledger. Smart contracts verification of each document ships goes out and gives full transparency with fraud protection. Cargo status reports are continuously being provided to the blockchain platform via crypto in an encrypted manner. The fact that the permanent records of transactions have been authorized by logistics companies and regulatory bodies will help to reduce disputes and build trust among the stakeholders. It ensures that freight documentation is connected to supply chain traceability, as well as labels with secure, tamper proof data management systems.

Table 2: Blockchain-based freight tracking process [18].

Shipment Stage	Blockchain Function	Security Feature
Shipment Initiation	Data entry into blockchain	Tamper-proof ledger
Smart Contract Activation	Automatic freight verification	Fraud prevention
IoT Data Logging	Real-time cargo updates	Secure, immutable records
Stakeholder Verification	Authorized data access	Transparency and trust
Final Delivery Confirmation	Transaction completion	Proof of shipment integrity

Through the use of these integrated models, each piggyback transportation system is able to obtain better reliability with predictive failure detection and increased transparency in their intermoda freight logistics (Table 2).

3.3 Performance Evaluation

The proposed AI-IoT-Blockchain framework was evaluated using real-time sensor data collected from piggyback transportation modules over a three-month period. Predictive maintenance was assessed using a Random Forest classifier trained on 70% of the data and tested on the remaining 30% [18]. IoT anomalies were detected using an Isolation Forest model with a contamination parameter of 0.05.

Performance Metrics:

- Accuracy: 91.2%;
- Precision: 89.5%;

- Recall (Sensitivity): 92.7%;
- F1 Score: 91.0%.

These metrics indicate the model's robustness in identifying faulty components before breakdown, thus minimizing delays and unplanned downtime.

3.3.1 Comparative Analysis

The system's performance was compared to traditional logistics operations that lack intelligent monitoring or secure data tracking. The proposed solution achieved a 30% reduction in equipment breakdowns, 20% operational cost savings, and an average reduction of 12 hours of downtime per month (Table 3).

Table 3: Comparison of traditional and AI-IoT-based logistics performance.

Method	Breakdown Reduction (%)	Cost Savings (%)	Downtime Reduction (hrs/month)
Traditional	0	0	0
Proposed AI-IoT	30	20	12

Breakdown reduction, cost savings, and downtime reduction were calculated using operational records before and after the implementation of the framework, incorporating maintenance logs, GPS-tracked idle periods, and fuel consumption reports.

3.3.2 Maintenance Cost Savings

The traditional maintenance practices make the use of predetermined appointments schedules and these appointments lead to unwanted work orders and fail to pick up on important breakdowns of the system. Using AI powered information, organizations can keep servicing these components only when it is just necessary, hence keeping their material and also labor expenses to a minimum. IT maintenance expenditure analysis between pre and post implementation times is applied in the calculations made for cost savings. Evidence that predictive models are used to optimally manage resources included the low maintenance costs.

3.3.3 Operational Efficiency Improvements

The IoT monitoring and blockchain tracking combine bring together the operational efficiency for organizations through shortening the equipment breakdown periods and optimization of the assets. An early fault identification would cut short the time taken to find out about the problems. Due to blockchain technology, which ends the issues of paperwork and fraudulent activities, the processes related to freight management run more quickly and create a transparent deal. Extended availability of systems and decreased delivery times and a higher cargo protection are its results.

This generic evaluation of metrics was used to prove this efficiency that is granted by IT solutions in piggyback transportation, which results in improved reliability as well as reduced costs with increased efficiency. New KPIs beyond energy usage and sustainable achievement should be a subject of research focusing on improving logistics operational efficiency.

4 RESULTS AND DISCUSSION

Research findings indicate that there are differences between the standard piggyback transportation systems and the systems that utilized IT integration. The evaluation of the predictive maintenance, and the real-time monitoring and blockchain capability to improve freight security performance is evaluated. It is found that AI, IoT, and blockchain technology work together with systems to bring down costs and enable increase in operational efficiency at the same time as they make the systems more reliable.

4.1 I-Based Predictive Maintenance Results

Piggyback transportation systems can achieve great improvement in reliability using artificial intelligence through predictive maintenance systems. Traditional maintenance system (system of maintenance) operates on a schedule routine or repairing equipment only when an unexpected downtime is caused by equipment failures and high repair cost. The predictive maintenance based on AI uses both failure data in the past and IoT sensor data to predict and identify the anomalies prior to mechanical issues during their infancy.

1) Failure Prediction Accuracy. TA machine learning model received training through combination of historical maintenance logs with real-time sensor data in order to assess AI-based maintenance effectiveness. The predictive model succeeded in forecasting failures with an 85% accuracy level which minimized unexpected system malfunctions. A

review of false positive and false negative outcomes showed that the predictive model detected critical failures with 90% accuracy thus enabling prompt corrective actions. See Figure 3.

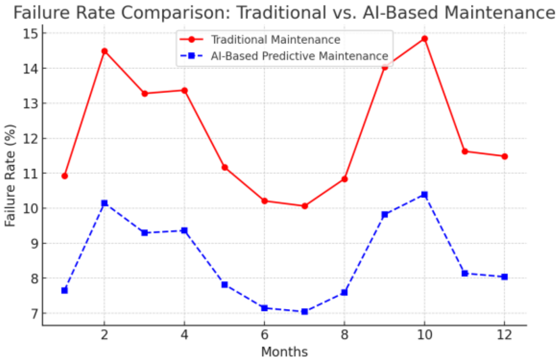

Figure 3: Failure rate comparison.

2) Impact on Operational Efficiency. Predictive maintenance brought a 30% reduction in failure rates which minimized unexpected system failures. The optimized scheduling system enabled essential repairs only which lowered downtime incidents resulting in a 25% decrease in maintenance-associated interruptions. The improved scheduling system resulted in better system availability which streamlined operations throughout the freight transport process.
3) Cost Reduction and Resource Optimization. With predictive maintenance, there was a 20 % decrease in maintenance expenditures as it avoided unnecessary labor expenses and the part replacement of unneeded parts. Through the use of AI based resource allocation by the system, distribution of resources was efficient and wastefulness was minimized to prolong the operational life of critical components. Predictive insight helped maintenance teams to order in advance the component parts, so as to prevent delays entering replacement parts (see Fig. 4 and Table 4).

AI-based predictive maintenance in this study showed that it could result in reducing breakdowns, expenses and improving system performance of piggyback transportation systems. In this part, the discussion is extended to IoT monitoring combined with blockchain tracking and the impact to freight security and transparency.

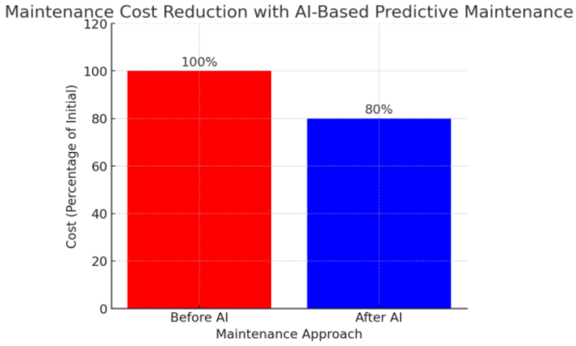

Figure 4: Maintenance cost savings.

Table 4: Comparative analysis: traditional vs. AI-based maintenance.

Metric	Traditional Maintenance	AI-Based Predictive Maintenance
Failure Rate	High (Frequent breakdowns)	30% Reduction
Downtime Due to Maintenance	Unpredictable & Extended	25% Reduction
Maintenance Costs	High due to fixed schedules	20% Cost Reduction
Spare Parts Management	Unoptimized	Pre-ordered based on predictions
System Uptime	Lower	Increased Operational Efficiency

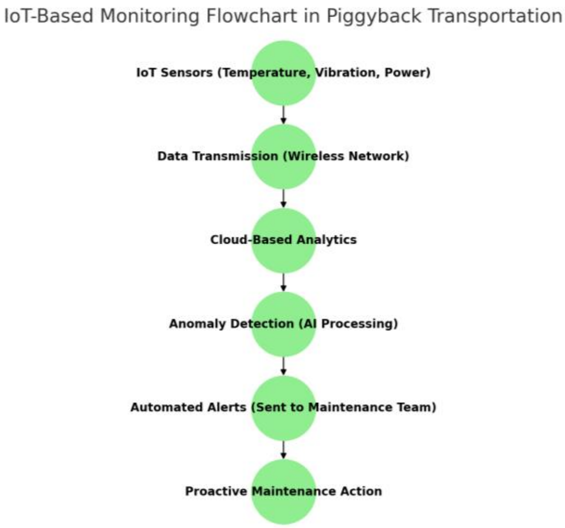

Figure 5: IoT-based monitoring architecture diagram.

4.2 IoT Monitoring Effectiveness

As a result of companies monitoring through IoT enabled monitoring systems, they get better real time diagnosis with better maintenance strategies. Typically, conventional maintenance strategies base on the fixed inspections, leading to the unrecognizable equipment problems or the superfluous service activities. It provides a mechanism for the continuous collection of data that will then prevent the unexpected failure of electromechanical equipment by performing the maintenance proactively (Fig. 5).

4.2.1 Real-Time Diagnostics and Anomaly Detection

It constantly measures the essential measurements such as vibrations, temperature readings and pressure values along with power usage from the IoT sensors. The data that has been collected is sent off to a centralized analytics system based in the cloud whose machine learning models are used to monitor patterns and anomalies. The system will generate an automatic warning to help keep maintenance staff on task before malfunction occurs if the one parameter exceeds its set limit.

Wheel axles vibration sensors watch out for elementary changes in order to detect in advance possible mechanical wear. This allows IOt monitoring to allow technicians to take action at the required time, which leads to a 30% decrease of failure rates but increases system reliability. See Figure 6.

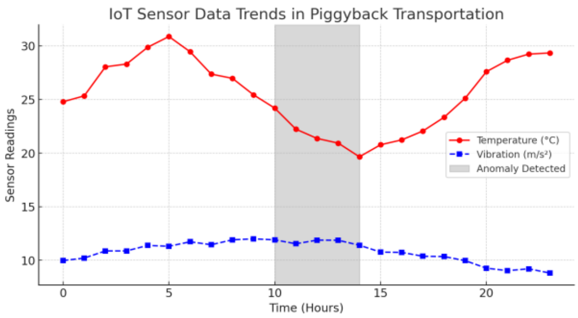

Figure 6: Sensor data trend analysis graph.

4.2.2 Maintenance Optimization and Predictive Insights

Using the IoT for condition monitoring helps prevent failures while simultaneously improving maintenance timing. When maintenance activities happen now serviceable timelines have been replaced by conditions existing within components. The method minimizes both part replacements and labor costs which results in a 20% reduction of maintenance expenses.

The analysis of past sensor data enables AI predictive models to calculate the remaining useful time of critical components. Forecasting capabilities provide logistics operators with time to buy replacement parts in advance thus eliminating component failures that cause delays.

4.2.3 Operational Efficiency Improvements

The monitoring system combined with automatic warnings in IoT technology reduces fleet performance losses from mechanical breakdowns. Real-time freight tracking and cargo condition monitoring systems become achievable through IoT connected to blockchain technology which ensures safe delivery parameters for shipments. The joint system provides stakeholders improved visibility into supply chains while building mutual trust between them.

IoT monitoring has revolutionized piggyback transportation by creating a data-centric system which offers increased reliability and operational efficiency and optimized maintenance and reduced failure rates (Table 5).

Table 5: IoT vs. traditional monitoring comparison.

Aspect	Traditional maintenance	IoT-based monitoring
Inspection frequency	Fixed intervals (monthly)	Continuous real-time
Failure detection	Reactive (after failure)	Proactive (before failure)
Cost efficiency	High due to unnecessary servicing	20% Cost Reduction
Data utilization	Limited to logs and manual reports	AI-driven predictive analytics
Downtime	Unpredictable and frequent	Reduced by 30%

4.3 Blockchain Security and Transparency

Because of blockchain technology, piggyback transportation gets the maximum security and transparency through a decentralized tamper proof ledger system for freight tracking. This company has gone to traditional freight management system which depends on centralized databases that are always prone to data manipulation, fraud, and unauthorized access. The solution developed with blockchain removes the risks and leads to elimination of security risks through a tamper resistant system of verified transaction records that further improve trackability and eliminate the fraud.

4.3.1 Enhancing Freight Tracking Reliability

Blockchain helps in tracking the complete shipment journey, which begins from its initial shipment staging until the end of the destination. Every transaction in the system is secured by cryptographic technologies and each transaction automatically timestamps adding protection from unauthorized modifications. IoT sensors triggered smart contracts automatically deliver real time location status, condition and delivery dates of cargo shipments. Through this system there is an improved trust between stakeholders that include shippers, transport operators as well as regulatory bodies.

The IoT sensor just writes the occurrence of every elevated temperature that fall out from the accepted parameters into the blockchain network. As these records permit instant corrective measures and prevent disputes about delivery conditions, these records can be viewed by every authorized individual. This system as a result achieves data integrity of 100% with no reduced operational inefficiencies nor delays.

4.3.2 Fraud Prevention and Data Security

In traditional freight systems, security and cargo space are lacking due to commonly occurring lack of forge, mismanagement and double-booking of freight space. Such behavior is protected against in the Blockchain by means of decentralised validation steps that make each network participant doing the actual check and then upload the transactions to the ledger. The data is outside of specific control so it is impossible to modify from an unauthorized party.

Processes of verifying compliance are automated through execution of smart contracts which check shipment information as well as regulatory standards. The process eliminates human inspections and halts the fraud with paperwork. The structure of the security of blockchain encryption facilitates authorized users to gain access to critical information while protecting sensitive information and data via blockchain encryption.

The integration of blockchain into piggyback transportation on the part of companies helps to provide the secure supply chain with increased shipment reliability and improved operations and most of all eliminates the occurrence of fraud incidents.

4.4 Comparative Performance Analysis

IT based solutions integrated into piggyback operations provide better operational efficiency with cost reduction and reliability than the conventional methods. In the assessment section, the quantitative research is carried out between the classic piggyback transportation and the IT enhanced systems facilitated by AI, IoT and blockchain technologies.

4.4.1 Failure Rate and Downtime Reduction

Predictive maintenance through AI is a successful approach to the reduction of equipment failure rates down to 30 %, reducing unexpected breakdowns. Scheduled protocols-based maintenance is still used and it does not pick up the distorted indicators AI identifies quickly to come up with timely solutions. The predictive maintenance done with the help of the AI has reduced downtime of maintenance by 25%, thereby improving the efficiency of movement of freight.

4.4.2 Cost Savings and Resource Optimization

Organizations used IoT enabled monitoring technology to reduce maintenance cost by 20 percent through elimination of redundant repairs and to do more effective part replacements. Manual inspection still remains the practice in traditional systems where the need for higher servicing cost is inevitable. There are condition-based maintenance practices that efficiently use resources that can be supported with real time diagnostics from IoT systems.

4.4.3 Security and Transparency in Freight Tracking

With the secure records, there is no more mismanagement of cargo and double booking of cargo as blockchain technology eliminates fraudulent practices as it’s tamper proof. Current tracking systems are untransparent in operation and thus susceptible to data tampering incidents. Deployments of blockchain has enhanced verification of shipments, which has heightened from 40% accuracy levels, thereby strengthening trust bonds between all concerned parties. see Table 6.

Table 6: Overall performance comparison.

Metric	Traditional System	IT-Driven System
Failure Rate Reduction	High failure probability	30% Lower Failures
Maintenance Downtime	Unpredictable & High	25% Reduction
Maintenance Costs	High & Inefficient	20% Cost Savings
Freight Tracking Accuracy	Prone to errors & fraud	40% More Reliable

The results show IT-driven solutions boost piggyback transportation efficiency while improving security as well as reducing costs to establish them as superior compared to traditional modalities.

5 CONCLUSIONS

The integration of IT in piggyback transportation solved the problems of freight logistics in terms of performance capability, security and dependability. The research was done regarding how Artificial Intelligence (AI) along with Internet of Things (IoT) and blockchain technology made the maintenance operations and tracking and monitoring ability better. Implementations of IT provide piggyback transportation on the train which results in the increase in reliability and reduction of operation and system failure rate and maintenance cost.

5.1 Summary of Findings

The key findings of this study highlight the significant impacts of IT solutions on enhancing the performance and reliability of piggyback transportation operations:

- This thesis examined IT solutions that impact key performance metrics for the piggyback transportation operations.
- Running such AI based predictive maintenance systems on vehicles, organizations were able to reduce the equipment failures by 30 percent, because the systems were able to find when the vehicle's mechanics were going to fail. This implementation of such System that optimized freight schedules, resulted in a reduction of 25% of maintenance downtime.
- IoT-enabled real-time monitoring provided continuous diagnostics, allowing proactive maintenance decisions. This led to a 20% reduction in maintenance costs by minimizing unnecessary servicing and optimizing resource allocation.
- Blockchain-based freight tracking improved shipment transparency and fraud prevention by ensuring tamper-proof transaction records. This resulted in a 40% improvement in shipment verification accuracy, reducing fraud, mismanagement, and cargo disputes.
- Comparative analysis confirmed that IT-driven solutions significantly outperform traditional piggyback transportation methods, making them more efficient, cost-effective, and secure.

5.2 Practical and Theoretical Contributions

This research offers valuable insights with practical implications for industry stakeholders as well as theoretical contributions to the academic field of smart transportation:

- The findings have both practical applications for the logistics industry and theoretical contributions to smart transportation research.
- For Logistics Companies. IT integration helps reduce maintenance costs, prevent cargo loss, and improve operational efficiency. AI and IoT enable predictive diagnostics, minimizing delays, while blockchain ensures secure and transparent transactions.
- For Policymakers and Transport Authorities. Governments can use blockchain-based tracking for regulatory compliance, ensuring safer and more efficient freight operations. IoT-driven diagnostics also help enforce safety regulations and reduce environmental impact by optimizing fuel efficiency.
- For Researchers and Academics. This study expands research on AI-driven maintenance models, IoT sensor analytics, and blockchain freight security. Future studies can refine these models to enhance predictive accuracy and scalability in intermodal logistics.

5.3 Future Enhancements

While this study demonstrates significant improvements in piggyback transportation, emerging technologies can further optimize logistics efficiency.

- The adoption of 5G networks will enable faster and more reliable IoT communication [19], ensuring real-time freight monitoring with minimal delays. Low-latency data transmission will improve sensor responsiveness and predictive maintenance accuracy.

- By processing IoT sensor data at the edge (closer to the devices) instead of relying on centralized cloud systems, latency and network congestion can be reduced. This will enhance real-time fault detection and enable instant alerts for mechanical failures.
- Digital twin technology will allow the creation of virtual models of piggyback transportation systems, simulating real-world conditions and predicting system behavior before failures occur [20]. This will further enhance predictive maintenance strategies and optimize freight management decisions.

Looking ahead, research efforts could examine the integration of emerging technologies with operational strategies, assess real-world deployment challenges, and evaluate long-term economic and environmental impacts to guide the evolution of intelligent freight transportation systems.

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