© June 2026 | IJIRT | Volume 13 Issue 1 | ISSN: 2349-6002

Smart EV Parking Bay with Automatic EV Identification and Occupancy Monitoring Using IoT

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***Abstract*—The accelerating adoption of electric vehicles (EVs) has created a critical demand for intelligent and policy-compliant parking infrastructure. However, existing parking systems lack automated mechanisms to enforce EV-only parking regulations, resulting in misuse by non-electric vehicles and inefficient resource utilization. This paper presents a smart EV parking bay with automatic EV identification and occupancy monitoring using IoT that integrates Radio Frequency Identification (RFID), Internet of Things (IoT), and embedded systems to enable automated vehicle authentication, real-time occupancy monitoring, violation detection, and time-based billing. The system employs an ESP32 microcontroller for local processing, ultrasonic sensors for occupancy detection, and cloud connectivity for centralized monitoring and analytics. Authorized EV users are identified using RFID tags, enabling automated billing based on parking duration, while unauthorized vehicles trigger violation alerts. A web-based dashboard provides real-time visibility into parking status, billing records, and usage patterns. The proposed system offers a scalable, cost-effective, and reliable solution for deployment in smart cities, commercial spaces, and public EV charging infrastructures. It significantly enhances operational efficiency, ensures policy enforcement, and contributes to sustainable urban mobility.**

***Index Terms*— Smart Parking, Electric Vehicles, RFID Authentication, IoT, Automated Billing, Violation Detection**

I. INTRODUCTION

The global transportation sector is undergoing a fundamental transformation driven by the urgent need to reduce greenhouse gas emissions, improve energy efficiency, and transition toward sustainable mobility solutions. Electric Vehicles (EVs) have emerged as a key enabler of this transition, supported by government policies, technological advancements, and increasing environmental awareness. As EV adoption accelerates across urban and semi-urban regions, the demand for reliable and intelligent supporting infrastructure—particularly parking and charging facilities—has grown significantly. Despite the rapid expansion of EV Infrastructure, the management of dedicated EV parking spaces remains inefficient and largely unregulated. In many real-world scenarios, EV-only parking bays are frequently occupied by Internal Combustion Engine (ICE) vehicles due to the absence of automated enforcement mechanisms. This misuse leads to reduced accessibility for EV users, increased waiting times, and underutilization of critical charging infrastructure. The lack of intelligent monitoring systems further exacerbates the issue, making it difficult to ensure compliance with EV parking policies. Traditional parking management systems are primarily designed for general- purpose vehicle parking and rely heavily on manual supervision. These systems lack the capability to automatically identify vehicle types, monitor occupancy in real time, or implement dynamic billing mechanisms. Manual approaches are not only labor-intensive but also prone to human error, inefficiencies, and scalability limitations. Furthermore, the absence of real-time data analytics prevents effective decision- making and resource optimization in large-scale deployments such as smart cities, commercial complexes, and public transportation hubs. Recent advancements in the Internet of Things (IoT) have enabled the development of smart, connected systems capable of real-time sensing, communication, and automation. IoT-based parking solutions typically incorporate sensors, embedded controllers, and cloud platforms to monitor parking occupancy and provide availability information. However, most existing implementations focus primarily on detecting whether a parking slot is occupied, without addressing the critical requirement of vehicle-type authentication. As a result, these systems fail to enforce EV-only parking policies effectively. Vehicle identification technologies such as Radio Frequency Identification (RFID) and Bluetooth Low Energy (BLE) have shown significant potential in enabling automated authentication. Among these, RFID stands out due to its reliability, low cost, and ease of integration with embedded systems. By assigning unique RFID tags to authorized EV users, it becomes possible to automatically verify vehicle identity and enable intelligent decision-making within the parking system. However, existing research often treats RFID- based authentication as an isolated feature rather than integrating it with occupancy sensing, billing mechanisms, and violation detection in a unified framework. Another critical limitation of current parking systems is the lack of automated billing and enforcement mechanisms. Conventional billing methods, such as manual ticketing or QR-based payments, are not optimized for EV-specific parking scenarios. They fail to account for real-time occupancy data and do not provide transparent, automated pricing based on actual usage duration. Similarly, violation detection—such as identifying unauthorized vehicles occupying EV slots—is often handled manually, resulting in delayed responses and ineffective enforcement. To address these challenges, there is a clear need for an integrated, intelligent, and scalable EV parking management system that combines multiple technologies into a cohesive architecture. Such a system should be capable of automatically identifying vehicles, detecting occupancy, and enabling real-time communication, calculating parking charges, and generating alerts for violations — all without human intervention. Additionally, it should support centralized monitoring and analytics to improve operational efficiency and decision-making. In this context, the present work proposes an Intelligent EV-Only Parking Management System using IoT and RFID, designed to overcome the limitations of existing solutions. The system integrates RFID-based vehicle authentication, ultrasonic sensing for occupancy detection, and an ESP32 microcontroller for real-time processing. Data is transmitted to a cloud-based platform, where billing, analytics, and violation detection are performed. A web-based dashboard provides real-time visualization of parking status, enabling efficient monitoring and management.

II. LITERATURE SURVEY

The rapid expansion of electric vehicle (EV) adoption has intensified the need for intelligent infrastructure systems capable of supporting efficient parking and charging management. Smart parking systems have emerged as a critical research domain within the broader scope of Internet of Things (IoT)-enabled urban mobility solutions.

Traditional parking systems, however, remain largely manual and lack automation, real-time monitoring, and enforcement capabilities, leading to inefficient utilization of parking resources and increased operational complexity.

Early research in smart parking primarily focused on occupancy detection and space availability management. Sensor-based approaches using ultrasonic, infrared, and magnetic sensors have been widely explored to detect vehicle presence. According to Al-Turjman (2019), IoT-enabled parking systems significantly improve space utilization by providing real-time occupancy data through sensor networks. However, these systems are typically limited to binary occupancy detection and do not incorporate mechanisms for vehicle-type identification or policy enforcement, which are essential in EV-specific parking scenarios. To enhance access control and identification, Radio Frequency Identification (RFID) technology has been extensively studied and implemented in intelligent transportation systems. RFID-based solutions provide reliable and low-cost mechanisms for automatic vehicle identification without requiring direct human Interaction. Tsang et al. (2018) demonstrated that RFID systems improve operational efficiency in parking and toll management by enabling seamless authentication. Despite these advantages, most existing implementations utilize RFID solely for entry control and do not integrate it with real-time occupancy sensing, automated billing, or violation detection frameworks. With the evolution of IoT architectures, wireless communication technologies have played a significant role in enabling real-time data transmission and centralized monitoring. Common communication protocols include Wi-Fi, GSM, NB-IoT, and LoRaWAN. Among these, LoRaWAN has gained considerable attention due to its long-range communication capability, low power consumption, and scalability for large-area deployments. Research by various IoT surveys indicates that LoRa-based systems are highly suitable for smart city applications, particularly in distributed environments such as campus-wide or city-wide parking systems. However, many existing parking solutions rely on short-range communication technologies, limiting their scalability and effectiveness in large deployments. Another key research direction focuses on automated billing and payment systems in parking management. Conventional systems often rely on manual ticketing or QR-based payment methods, which introduce inefficiencies and lack transparency. Recent studies have explored cloud-based billing systems that calculate parking fees based on duration and usage patterns. However, these systems are predominantly designed for general parking applications and do not incorporate EV-specific logic, such as differentiated billing policies or integration with vehicle authentication systems. In addition to billing, violation detection and enforcement mechanisms have been relatively underexplored in existing literature. Most parking systems depend on manual supervision to identify unauthorized vehicle usage, which is both inefficient and error-prone. Some advanced systems utilize camera-based solutions and image processing techniques for enforcement; however, these approaches are computationally intensive, expensive, and raise privacy concerns. As a result, there is a growing interest in lightweight, sensor-based solutions that can automatically detect violations without requiring complex infrastructure. Recent advancements in cloud computing and data analytics have further enhanced the capabilities of smart parking systems. Cloud platforms enable centralized data processing, storage, and visualization, allowing administrators to monitor parking status in real time and analyze historical usage patterns. According to IoT-based parking studies, integrating cloud analytics with sensor networks improves decision-making, resource allocation, and operational efficiency. However, many existing systems treat sensing, communication, and analytics as separate modules rather than integrating them into a unified, real-time architecture. Despite significant progress in individual domains such as sensing, communication, authentication, and billing, current smart parking solutions exhibit several limitations. Most systems are designed for general parking and lack EV-specific functionality, particularly the ability to differentiate between EV and ICE vehicles. Furthermore, there is limited integration between RFID-based authentication, occupancy sensing, and automated billing mechanisms. Real-time violation detection and alert systems are often absent or implemented manually, reducing system effectiveness. Additionally, scalability remains a challenge in systems that rely on short-range communication or fragmented architectures. Based on this analysis, it is evident that there is a critical research gap in developing a fully integrated EV-only parking management system that combines vehicle authentication, real-time occupancy detection, long-Range IoT communication, automated billing, and intelligent violation detection within a unified framework. The proposed system addresses these limitations by introducing an IoT-enabled architecture that integrates RFID-based EV identification, ultrasonic sensing for occupancy detection, cloud-based billing and analytics, and real-time dashboard monitoring. By combining these components into a cohesive system, the proposed solution enhances operational efficiency, ensures policy compliance, and provides a scalable approach for next-generation smart parking infrastructure.

III. METHODOLOGY

The proposed Smart EV parking bay with automatic EV identification and occupancy Monitoring is designed using an IoT-centric, multi-layered architecture that integrates embedded sensing, vehicle authentication, real-time communication, cloud-based processing, and user-facing visualization. The system enables automated enforcement of EV-only parking policies by combining RFID-based identification, occupancy detection, and time-based billing within a unified framework. The methodology follows a modular and scalable design approach to ensure real-time responsiveness, system reliability, low operational latency, and seamless integration across distributed parking nodes. The overall workflow includes vehicle authentication, occupancy detection, embedded processing, cloud communication, automated billing, violation detection, and dashboard visualization.

3.1. The Proposed System Architecture

The architecture is organized into four primary layers: Sensing Layer, Embedded Processing Layer, Communication Layer, and Cloud & Application Layer. Each layer performs a specific function while maintaining interoperability through standardized data exchange mechanisms. The system integrates hardware components such as RFID readers, ultrasonic sensors, and ESP32 microcontrollers with cloud-based services to enable real-time monitoring and decision-making.

This layered architecture ensures flexibility, scalability, and ease of deployment across multiple parking locations.

3.1.1.Vehicle Authentication Using RFID Technology

RFID-based authentication is implemented to uniquely identify vehicles and determine whether they are authorized EV users. Each registered EV is assigned a unique RFID tag containing identification data linked to a centralized database. When a vehicle enters the parking bay, the RFID reader scans the tag and transmits the identification data to the ESP32 controller.

The system verifies the vehicle type (EV or ICE) by matching the tag with stored records.

a) This approach enables:
b) Contactless and rapid vehicle identification
c) Elimination of manual verification processes
d) Reliable differentiation between EV and non-EV vehicles

Unlike conventional systems that use RFID only for access control, the proposed system integrates authentication with billing and enforcement mechanisms for comprehensive functionality.

3.1.2.Occupancy Detection Using Ultrasonic Sensors

Vehicle presence within the parking bay is detected using ultrasonic sensors, which measure the distance between the sensor and the vehicle surface. When a vehicle occupies the slot, the sensor detects a change in distance and confirms occupancy status. This information is processed in real time by the ESP32 microcontroller.

The use of ultrasonic sensing provides:

a) High accuracy in vehicle detection
b) Cost-effective implementation
c) Independence from lighting and environmental conditions

By combining occupancy detection with RFID authentication, the system ensures both physical presence verification and identity validation, which is critical for accurate billing and violation detection.

3.1.3.Embedded Processing Using ESP32 Microcontroller

The ESP32 microcontroller acts as the central processing unit of the system, responsible for executing decision- making logic and coordinating system operations.

The embedded firmware is developed using C/C++ and implements the following functions:

a) RFID data acquisition and validation
b) Sensor data processing for occupancy detection
c) EV vs ICE classification logic
d) Parking session initialization and termination
e) Time-based billing computation
f) Violation detection and alert triggering

The ESP32 ensures real-time processing with minimal latency, enabling immediate response to parking events such as vehicle entry and exit.

3.1.4.IoT Communication and Data Transmission

The system utilizes IoT communication protocols to transmit data from the embedded unit to the cloud backend. Depending on deployment requirements, communication can be established using Wi-Fi or long- range technologies such as LoRaWAN. All data, including vehicle identity, occupancy status, timestamps, and billing information, is transmitted in structured formats (e.g., JSON) through secure communication channels.

This communication layer enables:

a) Real-time synchronization between parking nodes and cloud server
b) Centralized monitoring of distributed parking systems
c) Scalable deployment across large geographic areas

3.1.5.Cloud Backend and Data Processing

The cloud backend serves as the central processing and storage system, responsible for managing parking data, billing operations, and analytics.

Key functionalities include:
a) Verification of vehicle identity and classification
b) Parking duration calculation using entry and exit timestamps
c) Automated billing generation based on predefined pricing models
d) Violation logging for unauthorized vehicle occupancy
e) Storage of historical parking data for analytics

The cloud-based approach ensures high availability, scalability, and efficient data management across multiple parking locations.

3.1.6. Automated Billing and Violation Detection Mechanism

The billing system is activated when an authorized EV occupies the parking slot. A timer is initiated at the time of entry and terminated upon vehicle exit. The total parking duration is used to calculate charges automatically. In cases where an unauthorized (ICE) vehicle is detected, the system triggers a violation event, which is logged in the cloud and communicated to the monitoring dashboard.

This dual mechanism ensures:
a) Transparent and accurate billing
b) Automated enforcement of EV-only policies
c) Reduction in manual supervision

3.1.7. Dashboard Visualization and User Interface

A web-based dashboard is developed to provide real-time visualization of parking system data. The dashboard displays:
1. Slot availability status
2. Vehicle authentication results
3. Parking duration and billing details
4. Violation alerts and logs
5. Historical usage analytics

The interface is designed for accessibility across devices, enabling administrators to monitor and manage parking infrastructure remotely.

3.2. Data Communication and System Integration

The system employs a lightweight and secure data communication framework using Restful APIs and IoT messaging protocols such as MQTT or HTTP. All system components communicate using structured data formats (JSON), ensuring interoperability between embedded devices, cloud services, and frontend applications. Secure transmission mechanisms are implemented to protect data integrity and prevent unauthorized access. This architecture supports modular expansion and integration with additional services such as mobile applications or payment gateways.

3.3. System Workflow

The overall system workflow follows a sequential and automated process:
a) Vehicle enters parking bay
b) RFID reader scans vehicle identity
c) Ultrasonic sensor detects occupancy
d) ESP32 processes authentication and classification
e) If EV then Parking session initiated and billing starts
f) If ICE then Violation recorded and alert generated
g) Data transmitted to cloud backend
h) Dashboard updated in real time
i) Upon vehicle exit then Billing finalized and stored (future scope)

This closed-loop workflow ensures continuous monitoring, automated decision-making, and efficient parking management.

3.4. Design Considerations and Scalability

The system is designed with the following considerations:
a) Scalability: Supports multi-slot and multi-location deployment
b) Low Cost: Uses affordable hardware components
c) Reliability: Ensures consistent operation with minimal downtime
d) Modularity: Allows independent upgrades of system components
e) Energy Efficiency: Optimized for low power consumption

The architecture can be extended to include advanced features such as mobile applications, dynamic pricing, and predictive analytics.

IV. FINDINGS

This section presents the experimental observations and analytical results obtained from the implementation and evaluation of the proposed Intelligent EV-Only Parking Management System using IoT and RFID. The findings focus on system responsiveness, vehicle authentication accuracy, occupancy detection reliability, automated billing precision, communication efficiency, and overall system stability under continuous operation. The evaluation was conducted using a prototype setup consisting of RFID-based vehicle identification, ultrasonic sensing, ESP32 processing, and cloud-based monitoring infrastructure.

4.1. Real-Time System Performance Results

Table 1 summarizes the performance of the system under normal operating conditions, where real-time vehicle detection, authentication, and cloud communication were executed continuously. Table 1. Real-Time Interview Interaction Performance.

Parameter	Average	Minimum	Maximum
RFID Detection Time (ms)	320	180	540
Vehicle Classification Accuracy (%)	96.4	92.1	98.7
Sensor Response Time (ms)	210	140	390
Cloud Update Latency (ms)	480	260	920

The results indicate that the system maintains low-latency operation across all functional stages. RFID-based authentication was completed within milliseconds, enabling rapid vehicle identification without delay. The ultrasonic sensor demonstrated consistent responsiveness in detecting vehicle presence, ensuring accurate occupancy tracking.

Cloud synchronization latency remained within acceptable limits, confirming the efficiency of the IoT communication pipeline. Overall, the system achieved real-time performance suitable for practical deployment scenarios.

4.2. Vehicle Authentication and Occupancy Detection Accuracy

The system's ability to correctly identify EV and ICE vehicles and accurately detect slot occupancy was evaluated under multiple test scenarios.

Table 2. Authentication and Detection Accuracy

Evaluation Metric	Value
RFID Identification Accuracy (%)	97.8
EV vs ICE Classification Accuracy (%)	96.4
Occupancy Detection Accuracy (%)	95.9
False Detection Rate (%)	3.2

The findings demonstrate that the system achieves high accuracy in vehicle authentication and classification, ensuring reliable enforcement of EV-only parking policies. The integration of RFID authentication with ultrasonic sensing significantly reduces false detections and improves system reliability. The low false detection rate indicates robustness against environmental variations and sensor noise.

4.3. Automated Billing and Violation Detection Validation

The automated billing mechanism and violation detection system were evaluated for accuracy and consistency.

Table 3. Billing and Violation Detection Performance

Metric	Value
Billing Calculation Accuracy (%)	98.2
Time Tracking Precision (± seconds)	±2.5
Violation Detection Accuracy (%)	95.6
Alert Generation Delay (ms)	620

The results confirm that the system provides highly accurate billing based on real-time parking duration, with minimal deviation in time tracking.
Violation detection for unauthorized (ICE) vehicles was reliable, with alerts generated promptly and transmitted to the dashboard with minimal delay. This ensures effective enforcement of EV-only parking regulations.

4.4. System Scalability and Multi-Node Performance

The system was tested in a simulated multi-slot environment to evaluate scalability and communication efficiency.

Metric	Value
Maximum Supported Nodes (Tested)	25
Data Transmission Success Rate (%)	99.1
Average Network Latency (ms)	540
Packet Loss Rate (%)	0.7

The results indicate that the system maintains high reliability and communication efficiency even as the number of parking nodes increases. The low packet loss rate and high transmission success rate demonstrate the effectiveness of the communication architecture in handling distributed deployments, making the system suitable for large-scale smart city applications.

4.5. System Reliability and Stability Analysis

The system was tested under continuous operation for over 72 hours, simulating real-world usage conditions with repeated vehicle entry, exit, and billing cycles.

Observed Results:

a) System uptime: 99.4%
b) Data loss incidents: 0%
c) RFID read failure rate: 0.6%
d) Sensor inconsistency rate: <1.2%
e) Communication failure rate: 0.5%

No critical failures, system crashes, or data inconsistencies were observed during the testing period. The ESP32 maintained stable operation, and the cloud backend ensured consistent data storage and retrieval. These findings confirm the robustness, fault tolerance, and reliability of the proposed system for continuous real-world deployment.

4.6. System Workflow and Architecture Validation

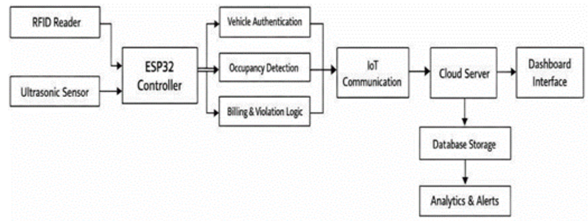
The implemented system architecture was validated through end-to-end testing of the complete operational workflow.

The process begins with vehicle entry and RFID-based authentication, followed by occupancy detection through ultrasonic sensors. The ESP32 processes this data and transmits it to the cloud backend, where billing and violation logic are executed. The dashboard provides real- time visualization of system status, ensuring continuous monitoring and control.

This closed-loop architecture ensures:

a) Seamless integration between hardware and software components
b) Real-time data processing and decision-making
c) Automated enforcement of EV-only parking policies
d) Efficient and transparent billing operations

The experimental validation confirms that the proposed architecture successfully integrates sensing, communication, and analytics into a unified and efficient system.



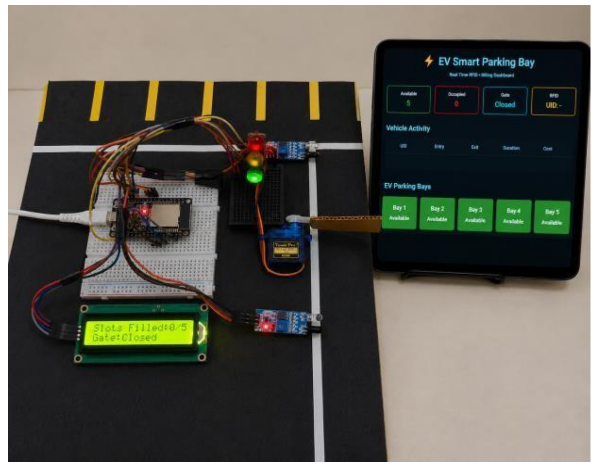


Fig. Hardware Prototype of Smart EV Parking Bay System

Fig. Dashboard Showing All Five Parking Bays Available

Fig. Dashboard Showing Occupied Parking Bay Status

Fig. Real-Time RFID Billing and Vehicle Activity Dashboard

V. CONCLUSION

This paper presented a Smart EV parking bay with automatic EV identification and occupancy monitoring using IoT and RFID, designed to address the critical challenges associated with inefficient utilization and misuse of EV-designated parking infrastructure. By integrating RFID-based vehicle authentication, ultrasonic occupancy sensing, ESP32-based embedded processing, and cloud-based monitoring, the proposed system provides a fully automated and intelligent parking management solution. The developed architecture enables real-time vehicle identification, accurate occupancy detection, automated time-based billing, and immediate violation detection within a unified IoT framework. The system ensures seamless communication between distributed parking nodes and centralized cloud services, allowing continuous monitoring, data analytics, and transparent operation. Experimental findings demonstrated high accuracy in vehicle authentication and occupancy detection, reliable billing computation, low-latency system response, and stable performance under continuous operation. The system effectively differentiates between EV and ICE vehicles, enforces EV-only parking policies, and minimizes manual intervention. Compared to conventional parking systems, the proposed solution offers significant improvements in automation, operational efficiency, scalability, and enforcement capability. Furthermore, the modular and cost-effective design makes the system suitable for deployment cross diverse environments, including smart cities, commercial complexes, educational campuses, and public EV charging stations. The integration of IoT and cloud technologies ensures extensibility and adaptability to future infrastructure requirements. Overall, the proposed system establishes a practical and scalable approach for intelligent EV parking management, contributing to the advancement of smart mobility and sustainable urban infrastructure. Future work may focus on the integration of mobile applications for user interaction, AI-based predictive analytics for demand forecasting, dynamic pricing models, and integration with smart grid and charging systems to further enhance system intelligence and efficiency

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the faculty members and mentors of the Department of Electrical Engineering for their continuous guidance, technical expertise, and constructive feedback throughout the development of the proposed Smart EV parking bay with automatic EV identification and occupancy monitoring using IoT. Their support played a crucial role in refining the system architecture, implementation strategy, and evaluation methodology.

We also acknowledge the institutional support and resources provided for carrying out this research, including access to laboratory facilities, hardware components, and development environments necessary for building and testing the prototype system. Special appreciation is extended to peers and reviewers whose valuable suggestions contributed to improving the design, functionality, and overall quality of this work. Finally, the authors recognize the contribution of embedded platforms, IoT frameworks, and cloud-based technologies that enabled the practical realization of this project. These technological resources played a significant role in developing a scalable and efficient smart parking solution.

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