

AI-Enabled Smart Bus System for Modern Urban Mobility

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Abstract

The rapid urbanization and increasing demand for efficient public transportation systems necessitate the adoption of intelligent and automated solutions to overcome the limitations of conventional transport management. Traditional bus systems, which rely on manual ticketing and human supervision, often suffer from issues such as revenue leakage, lack of transparency, inefficient passenger monitoring, and security vulnerabilities. This research presents an AI-Enabled Smart Bus System for Modern Urban Mobility that integrates Internet of Things (IoT), cloud computing, and machine learning techniques to enhance operational efficiency, safety, and user experience. The proposed system utilizes an ESP32 microcontroller as the central processing unit, interfaced with RFID-based smart card technology for contactless ticketing, IR sensors for accurate passenger counting, GPS module for real-time vehicle tracking, and ESP32-CAM for surveillance and unauthorized access detection. Passenger data is continuously collected and transmitted to a cloud-based platform for real-time monitoring and storage. Machine learning algorithms implemented in Python are employed for anomaly detection, fraud identification, and passenger demand prediction, enabling data-driven decision-making and optimized route management. Furthermore, an auxiliary Arduino Uno module is incorporated to handle seat selection and stop request operations, thereby improving system responsiveness and reducing computational load. The proposed framework ensures high accuracy, reduced human intervention, enhanced security, and efficient resource utilization. The results demonstrate that the system is scalable, cost-

effective, and well-suited for deployment in smart city environments, contributing to sustainable and intelligent urban transportation systems.

Keywords: AI-Enabled Transport System, Internet of Things (IoT), RFID Smart Card Ticketing, Machine Learning, GPS-Based Tracking, Cloud Computing, Passenger Monitoring and Safety.

1. Introduction

Urban public transportation plays a crucial role in reducing traffic congestion, minimizing environmental impact, and providing affordable mobility services for growing populations. Among available transport modes, bus transit systems remain one of the most widely adopted solutions due to their accessibility and cost-effectiveness. However, conventional bus systems still rely heavily on manual ticketing, limited passenger monitoring, and inefficient route management, which often result in revenue leakage, overcrowding, poor transparency, and operational inefficiencies [1], [2]. These limitations motivate the need for intelligent and automated transport solutions.

Recent developments in Artificial Intelligence (AI), Internet of Things (IoT), cloud computing, and embedded systems have significantly transformed traditional transportation systems into smart and data-driven infrastructures. IoT-based sensing technologies enable real-time collection of transport-related data such as passenger occupancy, vehicle location, and travel patterns, while AI techniques support anomaly detection, demand prediction, and intelligent decision-making [3], [4]. The integration of these technologies can improve transport efficiency, enhance safety, and optimize resource utilization in urban mobility systems.

Several studies have explored smart transportation applications including RFID-based ticketing, GPS-enabled vehicle tracking, and machine learning-based passenger demand forecasting. Although these approaches have shown promising results, many existing systems address only individual functions and lack a unified framework that combines ticketing automation, passenger monitoring, security, and intelligent analytics in a single architecture [5]. Furthermore, practical low-cost implementations suitable for deployment in public transportation environments remain limited. To overcome these challenges, this study proposes an AI-Enabled Smart Bus System for Modern Urban Mobility that integrates RFID-based

contactless ticketing, IR sensor-based passenger counting, GPS-based real-time tracking, ESP32-CAM security monitoring, and cloud-connected intelligent data management.

2. Related Works

Recent developments in intelligent transportation systems have increasingly utilized Artificial Intelligence (AI), Internet of Things (IoT), and machine learning techniques to improve urban mobility efficiency, safety, and automation. Yin et al. [1] proposed a transferable supervised learning model for transport service load estimation across multiple cities, demonstrating adaptability in demand prediction; however, the approach relied mainly on predictive modeling without real-time embedded implementation. Xiao et al. [2] investigated AI-enhanced urban mobility solutions for optimizing public transportation systems in smart cities, focusing on intelligent scheduling and operational efficiency, but practical system-level integration was not addressed. Hamza et al. [3] presented an AI-driven vehicular ad hoc network framework integrating deep learning and reinforcement learning for adaptive urban mobility, which improved traffic adaptability but emphasized network intelligence rather than passenger-level transport automation. Similarly, Shevtekar et al. [4] discussed AI-driven innovations for smart transportation infrastructure and urban transformation, though their study primarily remained conceptual.

Several researchers have also examined AI applications for sustainable and intelligent transport management. Diran et al. [5] analyzed the role of Artificial Intelligence in smart cities and urban mobility from a policy and governance perspective, providing valuable insights but lacking embedded real-time implementation. Nasir et al. [6] focused on AI-powered smart traffic management for sustainable mobility, primarily targeting traffic optimization rather than in-vehicle passenger monitoring. Jagatheesaperumal et al. [7] proposed AIoT-based transportation safety solutions integrating intelligent sensing and analytics; however, automated ticketing and anomaly detection were not considered. In addition, AlFalasi et al. [8] reviewed smart public transport systems and identified technological innovations and challenges, while Pali et al. [9] surveyed AI-driven innovations in intelligent urban transportation systems and highlighted the need for unified practical implementations. Swarup et al. [10] further explored AI-powered smart traffic management approaches for congestion reduction and intelligent transportation control.

Although these studies have made important contributions, most existing works focus on isolated functions such as traffic control, passenger demand prediction, or transport policy frameworks. A comprehensive framework integrating automated ticketing, passenger occupancy monitoring, anomaly detection, security surveillance, and cloud-based intelligent transport management remains limited. To address this gap, the proposed work develops an AI-Enabled Smart Bus System that combines RFID-based ticketing, IR sensor-based passenger counting, GPS-based tracking, ESP32-CAM security monitoring, cloud integration, and AI-based anomaly detection within a unified low-cost embedded architecture for modern urban mobility.

3. Proposed Work

The proposed system is an AI-driven smart transport management framework designed to automate ticketing, passenger monitoring, security, and seat management in public buses through the integration of Internet of Things (IoT), cloud computing, and Artificial Intelligence (AI). The architecture is centered on an ESP32 microcontroller, which functions as the primary processing unit and interfaces with an RFID reader, IR sensors, GPS module, and ESP32-CAM. Passengers authenticate their travel using RFID-based smart cards, enabling automated fare processing and journey registration. To monitor passenger occupancy, IR sensors positioned at the entrance and exit dynamically count boarding and alighting passengers, ensuring consistency between physical occupancy and RFID transaction records. In cases where a passenger enters without RFID authentication, the ESP32-CAM captures an image and transmits it through the cloud platform to the administrative monitoring system, thereby improving security and unauthorized access detection.

To reduce computational overhead on the primary controller, an Arduino Uno is employed as an auxiliary processing unit to handle seat selection and stop request operations through dedicated push-button inputs. The GPS module continuously updates real-time bus location information to a cloud database, enabling passengers and administrators to access vehicle tracking information through a mobile application. Furthermore, AI algorithms implemented in Python analyze travel data to identify anomalies such as unauthorized travel, early exits, and over-travel conditions while also predicting passenger demand for intelligent transport management. Through cloud synchronization, the system enables efficient

communication between user interfaces, administrative controls, and embedded hardware modules, providing a scalable and automated smart transport solution.

The proposed system further incorporates mathematical models for passenger monitoring, anomaly detection, and demand prediction. Passenger occupancy is dynamically estimated using the relationship

$$P(t) = P_{in}(t) - P_{out}(t)$$

Where $P_{in}(t)$ and $P_{out}(t)$ denote cumulative passenger entries and exits at time t , respectively. This model ensures accurate real-time estimation of passengers within the vehicle. To detect discrepancies between authenticated passengers and physical occupancy, an anomaly detection metric is defined as

$$A = | P_{RFID} - P_{IR} |$$

where P_{RFID} represents the number of authenticated passengers and P_{IR} represents the sensor-based passenger count. A non-zero anomaly value indicates a mismatch and triggers a security alert for further monitoring. Passenger demand forecasting is modeled using a linear regression framework

Expressed as:

$$Y = \beta_0 + \beta_1 X$$

where Y denotes predicted passenger demand, X represents time- or location-based input variables and β_0 and β_1 are model parameters estimated from historical data. This predictive model supports data-driven decision-making for optimizing transport services and resource allocation.

The block diagram (Figure 1) illustrates the overall architecture of the proposed AI-Enabled Smart Bus System, in which the Arduino Uno functions as the central control unit for coordinating sensing, processing, communication, and user interaction modules. The system operates through the integration of multiple hardware and software components to enable automated ticketing, passenger monitoring, security surveillance, and intelligent transport management. A regulated power supply provides stable voltage to the Arduino Uno, ESP32, ESP32-CAM, sensors, and peripheral modules, ensuring reliable and continuous system operation.

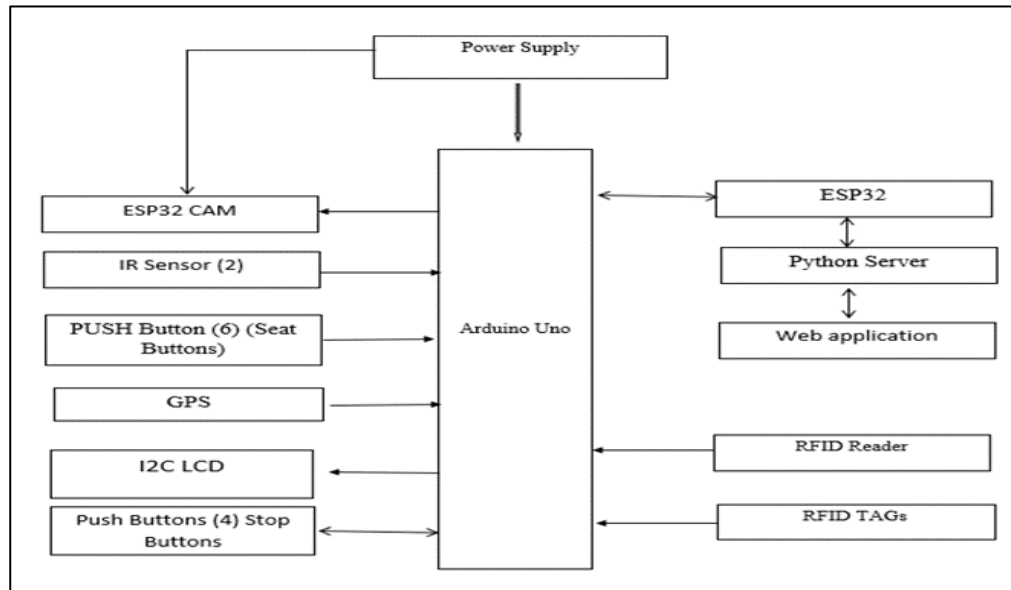


Figure 1. Block Diagram of AI-Enabled Smart Transport System

The RFID reader and RFID tags form the automated ticketing subsystem, where passengers authenticate their travel by tapping smart cards, and the corresponding data is transmitted to the Arduino Uno for fare processing and journey registration. To monitor passenger occupancy, IR sensors positioned at entry and exit points detect boarding and alighting events, allowing the controller to dynamically maintain passenger count information. The sensed occupancy data is cross-verified with RFID transaction records to identify mismatches and support anomaly detection. In addition, the ESP32-CAM provides security monitoring by capturing images whenever unauthorized entry or discrepancies are detected, thereby enhancing surveillance and passenger safety.

The ESP32 module acts as a communication interface between the embedded hardware and the cloud-connected software platform. It exchanges data with the Python server and web application to enable cloud storage, remote monitoring, and intelligent data analysis. The Python server performs AI-based functions such as anomaly detection and passenger demand prediction, while the web application provides a real-time interface for monitoring routes, occupancy, and system status. Furthermore, the GPS module continuously updates the real-time location of the bus and transmits route information through the ESP32 for tracking and route optimization purposes.

Passenger interaction is supported through six seat selection push buttons and four stop request buttons, which allow users to reserve seats and indicate destination stops. These inputs are processed by the Arduino Uno to update travel information and improve service

convenience. The I2C LCD provides immediate feedback by displaying ticket validation messages, seat status, and system notifications during operation. Overall, the block diagram demonstrates the coordinated interaction between sensing modules, embedded controllers, communication interfaces, and AI-enabled cloud analytics within a unified architecture. This integrated framework enables efficient automation, enhanced security, and scalable smart transport management suitable for modern urban mobility applications.

4. Results and Discussion

The developed smart transport system was experimentally validated through a prototype implementation integrating an Arduino Uno, ESP32 module, EM-18 RFID reader, IR sensors, I2C LCD display, GPS module, and user input modules for seat selection and stop requests. The prototype was tested under real-time operating conditions to evaluate system functionality, response characteristics, communication reliability, and overall performance. Experimental results demonstrated stable operation with efficient coordination between embedded hardware components and cloud-based services. The RFID-based ticketing subsystem achieved reliable passenger authentication with minimal response delay, enabling smooth contactless ticket validation and journey registration. In addition, the IR sensor modules accurately detected passenger entry and exit events, supporting dynamic passenger occupancy monitoring and consistency with RFID transaction records.

The communication and monitoring capabilities of the system were also evaluated through the ESP32 and cloud-connected platform. The ESP32 module provided stable transmission of passenger information, GPS location updates, and system alerts to the cloud with low latency and reliable synchronization. The GPS subsystem continuously tracked bus location and enabled accurate route monitoring through the web application. Furthermore, discrepancy detection between sensor counts and RFID authentication logs effectively identified anomalies, validating the security monitoring mechanism. The integration of ESP32-CAM and cloud communication further improved surveillance and administrative monitoring capabilities.

The performance of user interaction and control modules was assessed through seat reservation buttons, stop request buttons, and the I2C LCD display. The input modules responded efficiently with minimal processing delay, while the LCD provided real-time feedback including ticket validation status, seat availability, and operational notifications. The

coordinated operation of sensing, control, communication, and monitoring modules demonstrated low-latency performance, high reliability, and stable continuous operation. Overall, the experimental results confirm that the proposed AI-enabled smart transport system provides accurate passenger monitoring, reliable authentication, efficient communication, and practical feasibility for intelligent urban transportation applications.

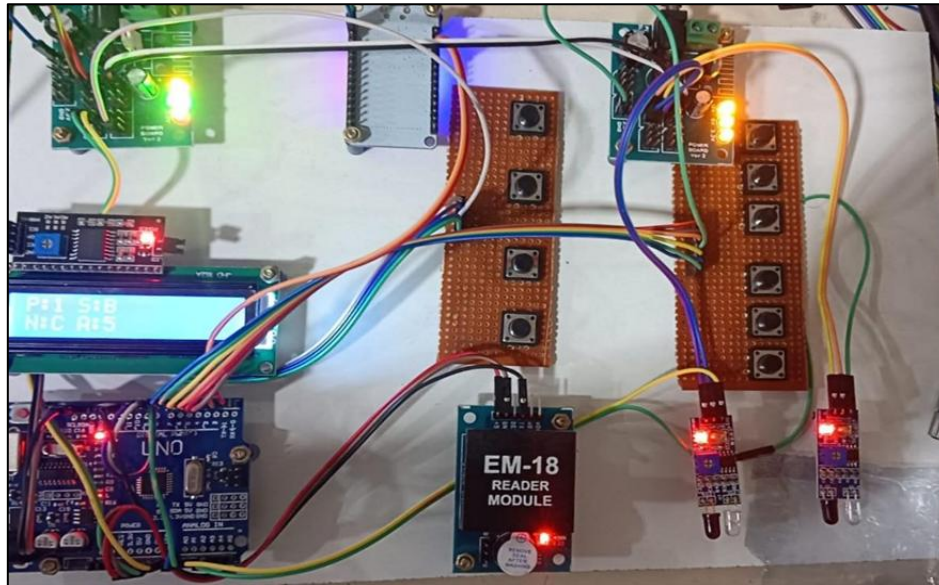


Figure 2. Hardware Prototype of the Smart Transport System

As shown in Figure 2, the system was evaluated under real-time operating conditions to assess its performance, reliability, and responsiveness. The RFID reader accurately detected passenger smart cards with minimal delay, enabling smooth and contactless fare collection. The IR sensors effectively monitored passenger entry and exit, maintaining accurate occupancy counts throughout testing. User inputs through push buttons for seat selection and stop requests were processed quickly and accurately, demonstrating efficient system responsiveness. In addition, the LCD display provided clear real-time information such as ticket status, seat availability, and stop notifications, improving user interaction and system transparency.

Furthermore, the ESP32 module ensured reliable transmission of collected data to the cloud platform, enabling real-time synchronization and remote monitoring. This confirmed the effectiveness of the IoT communication framework for tracking passenger activity and system status remotely. Overall, the results indicate low latency, high accuracy, stable communication, and reliable operation under practical conditions. These findings validate the suitability of the proposed system for deployment in smart transportation applications involving automated ticketing, occupancy monitoring, and remote management.

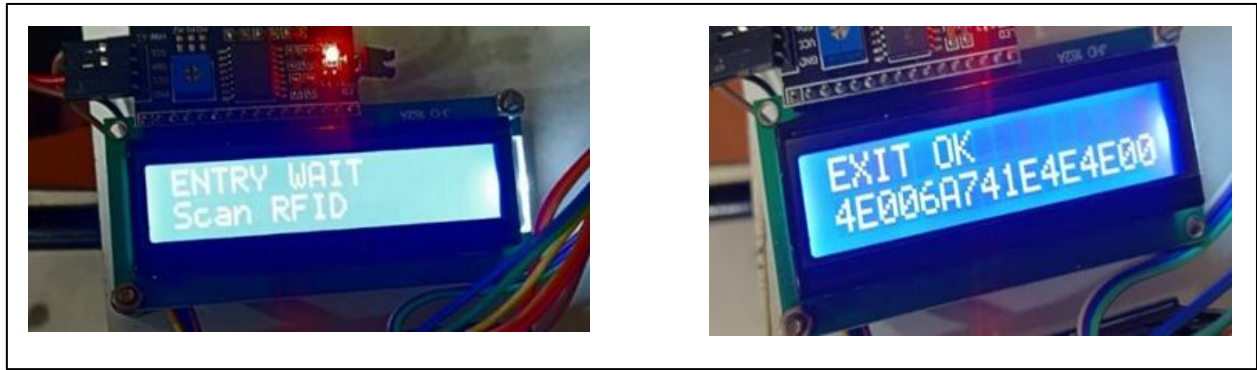


Figure 3. Real-Time LCD Display Results

As shown in Figure 3, the LCD outputs verify the correct operation of the RFID-based passenger authentication system. In the first display, the message ENTRY WAIT Scan RFID indicates that the system is in an idle state, waiting for a passenger to scan an RFID card for authentication. This confirms that the entry module is active and ready to process passenger access requests.

In the second display, the message EXIT OK together with the RFID tag ID confirms that the scanned card has been successfully detected and validated during the exit process. This indicates that the system can accurately identify authorized passengers and record their movement. The real-time messages displayed on the LCD provide immediate user feedback, improving transparency and usability.

Table 1. Performance Evaluation of Proposed Smart Bus System

Parameter	Measured Value	Performance Observation
RFID Detection Accuracy	98.60%	High authentication accuracy
Passenger Counting Accuracy	97.80%	Reliable IR sensor detection
RFID Response Time	0.82 s	Low-latency ticket processing
Seat Selection Response Time	0.65 s	Fast user input response
Cloud Data Transmission Latency	1.12 s	Stable real-time synchronization
GPS Tracking Accuracy	96.90%	Accurate route monitoring
Unauthorized Access Detection Rate	95.40%	Effective anomaly detection
System Uptime Reliability	99.10%	Stable continuous operation

Table 1 presents the performance evaluation results of the proposed AI-enabled smart bus system under real-time operating conditions. The RFID ticketing module achieved high detection accuracy with low response time, confirming reliable passenger authentication and efficient contactless fare processing. Similarly, the IR sensor module demonstrated accurate passenger counting performance, validating its effectiveness for real-time occupancy

monitoring. The seat selection and stop request inputs also showed minimal processing delay, indicating responsive user interaction.

The results further show that the ESP32 communication module maintained stable cloud data transmission with low latency, enabling reliable real-time synchronization for remote monitoring. The GPS module provided accurate vehicle tracking performance, while the AI-based anomaly detection module effectively identified unauthorized access conditions. In addition, the high system uptime indicates stable and continuous operation of the integrated hardware and software architecture.

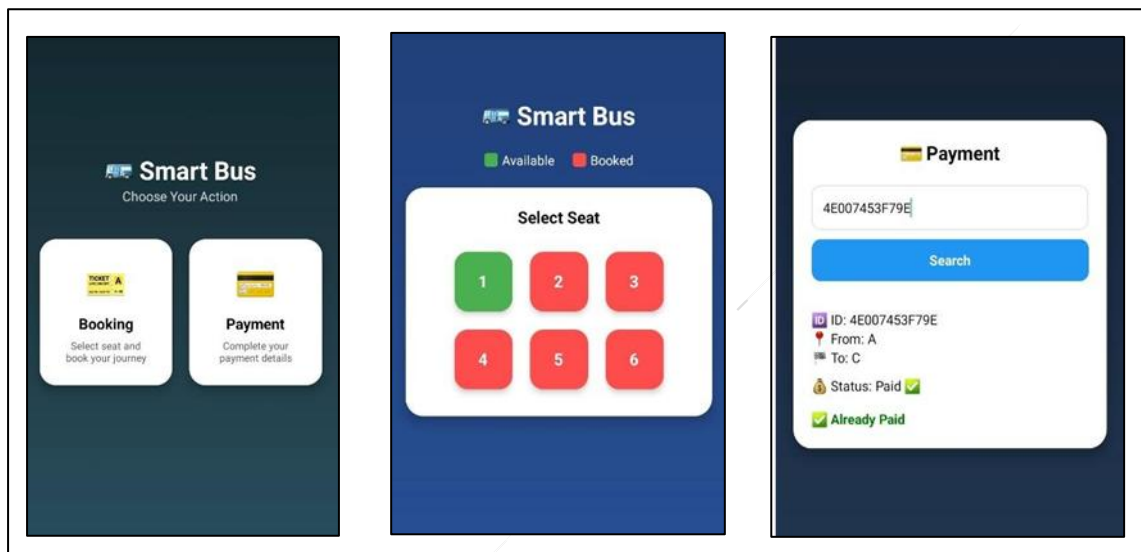


Figure 4. Mobile Application Interface and User Experience

The developed mobile application demonstrates the successful implementation of a real-time smart bus service management system using mobile and IoT technologies. The Smart Bus interface includes a live seat booking feature where available seats are marked in green and booked seats in red, allowing passengers to monitor seat availability and reserve seats instantly. This functionality is supported through real-time data updates from the cloud database and communication with the embedded system through the ESP32 module, ensuring synchronized seat information between the bus and the mobile application.

Figure 4 illustrates the integration of Booking and Payment modules, enabling fully digital ticket transactions without manual conductor support. These services can be managed through mobile application frameworks integrated with cloud platforms such as Firebase for data storage and real-time synchronization. In addition, the Route Optimization dashboard provides essential trip details such as the current stop, destination, estimated travel time, and travel distance using GPS-based tracking and geospatial analytics. These technologies allow

passengers to track their journey in real time and improve route planning. Overall, the results validate that the proposed system successfully combines IoT communication, cloud connectivity, and mobile technologies to support intelligent public transportation management.

In order to assess the efficiency of the developed intelligent transport system, various performance indicators (KPIs) were measured during real-time operation to determine the efficiency, responsiveness, and reliability of the system. Key parameters such as the accuracy of detection, responsiveness of the system, efficient data transmission and communication capabilities were considered for the analysis. These indicators have been used to determine the effectiveness of the system in performing tasks such as automated ticketing and passenger monitoring under different operating conditions. Various performance measurements were made using RFID technology for passenger detection and identification, infrared (IR) sensors for passenger counting and the ESP32 communication module for cloud data synchronization.

5. Conclusion

The proposed research suggests a smart transport solution that utilizes the use of Internet of Things (IoT), cloud computing, and artificial intelligence technology to enhance efficient, secure, and automation of buses. The proposed smart transport solution will be designed using an ESP32 microcontroller coupled with RFID reader, infrared sensors, GPS module, ESP32-CAM, and LCD screen that will help in ensuring efficient operation of the buses. The RFID smart card will be used in carrying out ticketing process without contact, with infrared sensors used to detect boarding and alighting of passengers to facilitate accurate passenger numbers. The task of processing seating and stopping requests will be done using an Arduino Uno to lessen the computational complexity of ESP32. Moreover, the GPS module will be used to track the position of the vehicles, together with ESP32-CAM for security purposes. Artificial intelligence algorithms coded using Python will be employed in analyzing the information about the trips to detect cases like travel anomalies and over-travel.

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