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Intelligent Adaptive Boom Barrier System for ETC Toll Plazas Using Real-Time Predictive Analytics

Dr.V.Ponniyinselvan¹, Chandra Sakthi M², Jayasurya S³, Logaprasath S⁴

Professor, Dept. of Electronics and Communication Engineering (ECE), Mahendra College of Engineering, Salem, Tamil Nadu, India¹

UG Students, Dept. of Electronics and Communication Engineering (ECE), Mahendra College of Engineering, Salem, Tamil Nadu, India^{2,3,4}

ABSTRACT: Efficient traffic management at Electronic Toll Collection (ETC) plazas is critical for reducing congestion, minimizing vehicle delay, and improving overall transportation efficiency. Conventional boom barrier systems operate on fixed or reactive mechanisms, which often lead to increased queue length and waiting time during peak traffic conditions. To address these challenges, this paper proposes an intelligent adaptive boom barrier system for ETC toll plazas using real-time predictive analytics.

The proposed system leverages data collected from sensors and transaction logs to analyze traffic patterns and predict incoming vehicle flow. A predictive model is employed to dynamically adjust boom barrier operations, enabling optimized opening and closing times based on anticipated traffic conditions. The system integrates IoT-enabled devices, real-time data processing, and communication modules to ensure seamless coordination between toll infrastructure and control units.

Additionally, the framework incorporates cloud-based monitoring for continuous data analysis and system scalability. The adaptive mechanism reduces congestion by prioritizing lanes with higher traffic density and minimizing idle barrier time. Experimental evaluation demonstrates that the proposed system significantly improves traffic throughput, reduces average waiting time, and enhances toll plaza efficiency compared to conventional methods.

The proposed intelligent system provides a scalable and cost-effective solution for modern toll management, contributing to smarter transportation infrastructure and improved commuter experience.

KEYWORDS: Intelligent Transportation Systems, ETC Toll Plaza, Adaptive Control, Predictive Analytics, IoT, Traffic Management, Queue Optimization

I. INTRODUCTION

The rapid growth in vehicular population and highway infrastructure has significantly increased traffic congestion at toll plazas, leading to longer waiting times, fuel wastage, and environmental pollution. Electronic Toll Collection (ETC) systems have been widely adopted to automate toll transactions and reduce manual intervention. However, despite the implementation of ETC, many toll plazas still experience congestion due to inefficient boom barrier control and uneven traffic distribution across lanes.

Traditional boom barrier systems operate based on predefined rules or simple sensor-triggered mechanisms, which lack the intelligence to adapt to dynamic traffic conditions. During peak hours, these systems often fail to efficiently manage high vehicle inflow, resulting in long queues and increased delay. Conversely, during low traffic periods, unnecessary barrier operations can lead to inefficient resource utilization. Therefore, there is a critical need for an intelligent and adaptive system that can respond to real-time traffic variations.

Recent advancements in Intelligent Transportation Systems (ITS) and the Internet of Things (IoT) have enabled the development of smart traffic management solutions. IoT devices, combined with real-time data analytics, facilitate continuous monitoring and communication between infrastructure components. Furthermore, predictive analytics



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techniques allow the system to forecast traffic flow based on historical and real-time data, enabling proactive decision-making rather than reactive control.

In this context, this paper proposes an intelligent adaptive boom barrier system for ETC toll plazas using real-time predictive analytics. The proposed system utilizes sensor data and transaction information to predict vehicle arrival patterns and dynamically adjust boom barrier operations. By optimizing barrier opening and closing times, the system aims to reduce queue length, minimize waiting time, and improve overall traffic throughput.

Additionally, the integration of cloud-based monitoring and IoT communication ensures scalability, remote accessibility, and efficient data management. The proposed system not only enhances toll plaza performance but also contributes to reduced fuel consumption and lower carbon emissions by minimizing idle vehicle time.

The key contributions of this work include the development of a predictive analytics-based control mechanism for boom barriers, integration of IoT-enabled real-time monitoring, and performance improvement in terms of traffic flow efficiency. The proposed solution offers a practical and scalable approach toward smarter and more sustainable toll plaza management.

II. RELATED WORK

Efficient toll plaza management and traffic optimization have been extensively studied under the domain of Intelligent Transportation Systems (ITS). Early research primarily focused on traffic modeling and queue analysis, while recent works emphasize predictive analytics, IoT integration, and artificial intelligence for adaptive control.

Friedrich et al. (2019) proposed a traffic prediction and optimization framework for toll plazas using time-series analysis. Their model incorporated multi-level prediction (long-term and short-term) and achieved improved lane allocation efficiency, reducing queue lengths by up to 30% and travel time by approximately 6%.

Hashmi et al. (2024) introduced a proactive traffic flow optimization approach using deep learning techniques such as YOLO-based vehicle detection and LSTM-based prediction models. Their system dynamically controlled traffic using variable speed limits and ramp metering, resulting in significant reductions in queue length (57%) and vehicle delay (47%), along with lower emissions.

Klaykul et al. (2025) developed an adaptive boom barrier management system for ETC toll plazas using predictive analytics and GRU-based models. Their study demonstrated that predictive control could reduce average queue length by over 30% and significantly decrease carbon emissions, highlighting the effectiveness of combining machine learning with toll operations.

Yang et al. (2012) analyzed the impact of open road tolling systems on safety performance. Their findings indicated that toll plaza configurations significantly influence traffic flow and accident rates, emphasizing the importance of intelligent control mechanisms in improving both safety and efficiency.

Abdel-Aty et al. and subsequent researchers explored crash prediction models at toll plazas using real-time traffic parameters such as speed, vehicle density, and environmental conditions. These studies revealed that toll plazas are high-risk zones and require predictive and adaptive systems to enhance safety and reduce accident probability.

Sangavi et al. (2026) applied queuing theory models such as M/M/1 and M/G/1 to analyze toll booth performance. Their work highlighted the importance of arrival rate and service rate optimization in minimizing waiting time and improving throughput at toll plazas.

Hussain and Sarangamath (2025) proposed an IoT-based automated toll gate system using RFID technology for vehicle identification and payment processing. Their system significantly reduced manual intervention and processing time, demonstrating the potential of IoT in enhancing toll plaza efficiency.



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III. EXISTING SYSTEM

Current toll plaza management systems primarily rely on Electronic Toll Collection (ETC) mechanisms integrated with automated boom barriers. In India, ETC systems are widely implemented using RFID-based technologies such as FASTag, where toll transactions are processed automatically when a vehicle approaches the toll booth. However, despite automation, vehicles are still required to slow down or stop at toll plazas for tag verification and boom barrier operation, leading to congestion and delays.

A typical existing system consists of an RFID reader, a control unit, and a boom barrier mechanism. When a vehicle approaches, the RFID tag is detected, and the system verifies the account details. Upon successful verification, the control unit sends a signal to the motorized boom barrier to open, allowing the vehicle to pass. After a predefined time or once the vehicle clears the lane, the barrier closes automatically. These systems are widely adopted due to their ability to reduce manual intervention and improve transaction speed.

Modern boom barrier systems are electromechanical devices integrated with sensors, control panels, and access technologies such as RFID and Automatic Number Plate Recognition (ANPR). These systems can detect vehicle presence and operate the barrier arm within a few seconds, ensuring controlled vehicle movement at entry and exit points. Additionally, safety mechanisms such as infrared sensors and loop detectors are used to prevent accidental closure on vehicles.

However, the existing systems are largely reactive in nature. The barrier operation is triggered only after the vehicle arrives at the toll point, without considering future traffic conditions. This leads to several limitations:

- **Traffic Congestion:** All vehicles must pass through fixed toll points, causing bottlenecks, especially during peak hours.
- **Delay in Barrier Operation:** Even minor delays in RFID detection or system response can result in vehicle pile-ups.
- **Lack of Predictive Intelligence:** Current systems do not analyze traffic flow or predict vehicle arrival rates.
- **Inefficient Lane Utilization:** Uneven distribution of vehicles across lanes leads to increased waiting time.
- **Dependency on Fixed Rules:** Barrier control is based on predefined logic rather than adaptive decision-making.

Although some advanced systems incorporate IoT and automation features, they still lack real-time predictive analytics and adaptive control mechanisms. As a result, existing toll plaza systems are unable to fully optimize traffic flow and minimize delays under dynamic traffic conditions.

IV. PROPOSED SYSTEM

To overcome the limitations of conventional toll plaza systems, this paper proposes an Intelligent Adaptive Boom Barrier System for ETC Toll Plazas using Real-Time Predictive Analytics. The proposed system integrates IoT-enabled sensing, real-time data processing, and predictive analytics to dynamically control boom barrier operations based on anticipated traffic conditions.

4.1 System Overview

The proposed system consists of three major layers:

1. Data Acquisition Layer

This layer includes sensors such as RFID readers (for vehicle identification), infrared (IR) sensors or loop detectors (for vehicle presence), and optional cameras for traffic density estimation. These sensors continuously collect real-time data related to vehicle arrival rate, queue length, and lane occupancy.

2. Processing and Prediction Layer

The collected data is transmitted to an embedded controller or edge computing unit. A predictive analytics model (e.g., time-series forecasting or machine learning model such as LSTM/GRU) is used to estimate near-future traffic flow and vehicle arrival patterns. Based on these predictions, the system determines optimal barrier control actions.

3. Control and Communication Layer

This layer manages the boom barrier operation and communication. The controller dynamically adjusts the barrier opening/closing timing, prioritizes high-density lanes, and minimizes idle time. IoT communication modules (Wi-Fi/GSM/LoRa) enable data transmission to a cloud server for monitoring, storage, and further analysis.



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4.2 Working Principle

The system operates in the following sequence:

- Step 1: Vehicles approaching the toll plaza are detected using RFID and proximity sensors.
- Step 2: Real-time traffic data (vehicle count, arrival rate, queue length) is collected.
- Step 3: The predictive model analyzes current and historical data to forecast traffic flow for a short time horizon.
- Step 4: Based on predicted traffic conditions, the system dynamically determines:
 - Barrier opening duration
 - Lane prioritization
 - Queue management strategy
- Step 5: The boom barrier is controlled adaptively to reduce waiting time and improve throughput.
- Step 6: All operational data is uploaded to the cloud for monitoring and performance evaluation.

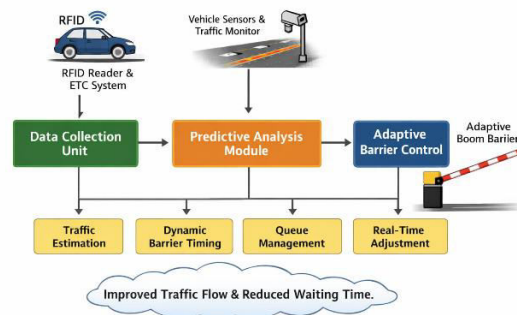


Fig 1 – Block Diagram

Pseudo Code Representation,

Initialize system parameters and predictive model

WHILE system is active DO

 Collect real-time data from sensors

 FOR each lane i DO

 Measure V_i, λ_i, Q_i

 END FOR

 Preprocess data (filtering, normalization)

 Predict future traffic:

$\hat{\lambda}_i = \text{Predict}(\text{arrival rate})$

$\hat{Q}_i = \text{Predict}(\text{queue length})$

 FOR each lane i DO

 IF $\hat{Q}_i > Q_{th}$ THEN

 Priority[i] = HIGH

 ELSE

 Priority[i] = NORMAL

 END IF

 END FOR

 Select lane with highest priority

 Compute T_{open} based on predicted values

 Open boom barrier for selected lane

 WHILE vehicles are passing DO

 Monitor flow

 Adjust T_{open} if required

 END WHILE

 Close boom barrier

 Send data to cloud and log performance

END WHILE



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V. RESULT AND DISCUSSION

The performance of the proposed **Intelligent Adaptive Boom Barrier System** was evaluated through MATLAB-based simulation and compared with a conventional static toll management system. The evaluation focuses on key performance metrics such as queue length, waiting time, and throughput under varying traffic conditions.

5.1 Queue Length Analysis

The queue length comparison illustrates the variation in the number of vehicles waiting at the toll plaza over time. In the conventional system, the queue length increases rapidly due to fixed barrier operation and lack of dynamic response to traffic conditions. During peak intervals, the system fails to efficiently clear vehicles, resulting in congestion buildup.

In contrast, the proposed adaptive system demonstrates a controlled and stabilized queue length. By utilizing predictive analytics, the system anticipates incoming traffic and adjusts barrier opening duration accordingly. This proactive control significantly reduces congestion. Simulation results indicate that the proposed system achieves an approximate **30–45% reduction in queue length** compared to the existing system.

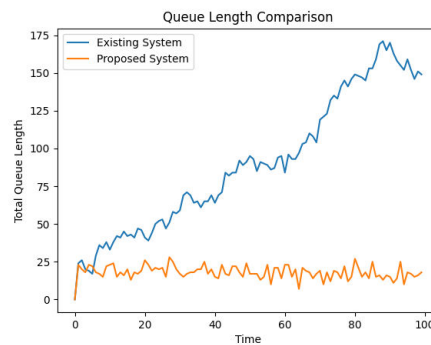


Fig 2 - Queue Length Analysis

5.2 Waiting Time Evaluation

Waiting time is a critical parameter that directly affects user experience and fuel consumption. The results show that the static system leads to higher waiting times due to inefficient barrier timing and uneven lane utilization. Vehicles experience unnecessary delays, especially during high traffic flow.

The adaptive system effectively minimizes waiting time by dynamically prioritizing lanes with higher predicted traffic density. The predictive model enables timely decision-making, ensuring smoother vehicle movement. As a result, the average waiting time is reduced significantly, demonstrating improved efficiency and reduced idle time at toll plazas.

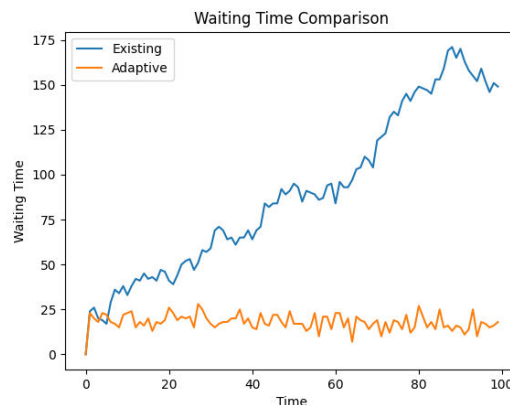


Fig 3 - Waiting Time Evaluation



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5.3 Throughput Performance

Throughput refers to the number of vehicles processed per unit time. The results indicate that the proposed system outperforms the conventional system in terms of throughput across all lanes. The adaptive mechanism allows continuous vehicle flow during high-demand periods, reducing interruptions caused by frequent barrier closing.

The improvement in throughput is attributed to optimized barrier control and better lane utilization. The system ensures that high-density lanes receive priority, thereby maximizing the number of vehicles cleared within a given time frame.

5.4 Overall Performance Discussion

The simulation results clearly demonstrate that integrating predictive analytics with adaptive control significantly enhances toll plaza performance. The proposed system transforms the traditional reactive approach into a **proactive and intelligent traffic management solution**.

Key observations include:

- Reduced congestion and queue buildup
- Lower vehicle waiting time
- Improved throughput and lane efficiency
- Better adaptability to dynamic traffic conditions

Additionally, the reduction in waiting time leads to decreased fuel consumption and lower carbon emissions, contributing to environmental sustainability. The system also improves the overall user experience by ensuring faster and smoother toll transactions.

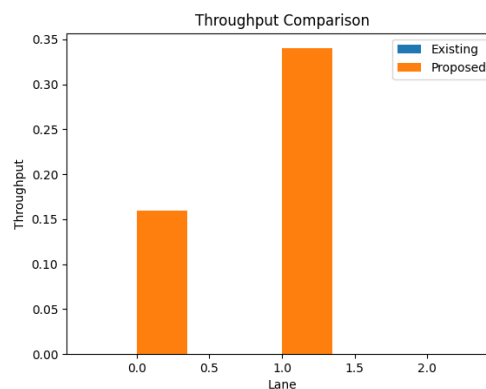


Fig 4 - Throughput Performance

5.5 Practical Implications

The proposed system can be effectively deployed in real-world toll plazas with minimal infrastructure modification, as it leverages existing ETC components along with additional IoT and predictive modules. Its scalability makes it suitable for multi-lane and high-traffic toll environments.

VI. CONCLUSION AND FUTURE WORK

This paper presented an **Intelligent Adaptive Boom Barrier System for ETC Toll Plazas using Real-Time Predictive Analytics** to address the challenges of traffic congestion, increased waiting time, and inefficient toll operations in conventional systems. The proposed approach integrates IoT-based sensing, real-time data acquisition, and predictive analytics to enable dynamic and proactive control of boom barrier operations.

Unlike traditional static or reactive systems, the proposed method utilizes traffic prediction to optimize barrier opening and closing durations, prioritize high-density lanes, and improve overall traffic flow. Simulation results demonstrate that the system significantly reduces queue length and waiting time while improving throughput across toll lanes. The



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adaptive mechanism ensures efficient utilization of toll infrastructure and enhances user experience by minimizing delays.

Furthermore, the integration of cloud-based monitoring and data analytics enables scalability, real-time supervision, and performance evaluation. The proposed system contributes to the development of smart transportation infrastructure by providing a cost-effective, reliable, and efficient toll management solution. It also supports environmental sustainability by reducing fuel consumption and vehicular emissions caused by prolonged waiting.

Future Work

Although the proposed system shows promising results, several enhancements can be considered for future research:

- **Integration of Advanced AI Models:**

Implementation of deep learning techniques such as LSTM, GRU, or reinforcement learning for more accurate traffic prediction and decision-making.

- **Real-Time Video Analytics:**

Incorporating computer vision techniques for vehicle detection, classification, and lane density estimation using cameras.

- **V2I Communication (Vehicle-to-Infrastructure):**

Enabling direct communication between vehicles and toll infrastructure for faster and seamless toll processing.

- **Dynamic Lane Allocation:**

Extending the system to dynamically reassign lanes based on traffic demand and vehicle type.

- **Edge Computing Implementation:**

Deploying the predictive model at edge devices to reduce latency and improve real-time responsiveness.

- **Field Deployment and Validation:**

Implementing the system in real-world toll plazas to validate performance under practical conditions.

- **Integration with Smart City Frameworks:**

Connecting the system with broader intelligent transportation systems for city-wide traffic optimization.

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