IJARCCE ISSN (O) 2278-1021, ISSN (P) 2319-5940

International Journal of Advanced Research in Computer and Communication Engineering

Impact Factor 8.102 ⁙ Peer-reviewed & Refereed journal ⁙ Vol. 14, Issue 4, April 2025

DOI: 10.17148/IJARCCE.2025.14422

GPS Based Toll System Simulation

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Abstract: This paper presents an innovative GPS-based toll collection system developed for the Mumbai-Pune Expressway, aimed at eliminating physical toll booths through the integration of geofencing and real-time GPS tracking. Leveraging OpenStreetMap (OSM) data processed via QGIS, the system defines virtual toll zones and calculates charges dynamically using the Haversine formula. Machine Learning models are incorporated to optimize toll pricing and enable automated remote fee processing. A web-based dashboard facilitates real-time monitoring and digital payments, enhancing user convenience and operational transparency. Experimental results demonstrate a 92% prediction accuracy, 30% reduction in computational overhead, and 40% cost savings compared to traditional tolling infrastructure. The proposed system showcases a scalable, efficient, and storage-free alternative for modernizing toll collection practices.

Keywords: GPS Tolling, Geofencing, Dynamic Pricing, Machine Learning, Smart Transportation, Cloud-based Toll Collection, Real-time GPS Monitoring.

I. INTRODUCTION

With the rapid growth of urbanization and a continuous rise in vehicular density on highways, traditional toll collection systems are becoming increasingly inadequate in addressing modern transportation demands. Conventional methods such as manual toll booths and RFID-based systems, which were once seen as innovative, are now contributing to severe traffic bottlenecks, excessive fuel consumption, and prolonged travel times. These systems typically require vehicles to slow down or stop entirely at checkpoints, disrupting the flow of traffic and leading to higher carbon emissions. Furthermore, the infrastructure and manpower required to operate and maintain these toll plazas impose significant financial burdens on government agencies and transportation authorities.

In light of these challenges, there is a growing need for smarter, more efficient toll collection solutions. The evolution of GPS (Global Positioning System) technology, when combined with geofencing capabilities, has opened up new opportunities for transforming toll systems into fully automated and seamless operations. GPS-based tolling eliminates the necessity for physical contact points by using virtual perimeters—called geofences—to monitor when a vehicle enters or exits a designated toll zone. Through the use of distance-based calculation algorithms, such as the Haversine formula, the system determines the appropriate toll charge based on the actual distance traveled. Charges are then automatically deducted from the user's digital wallet or prepaid account, thus removing the need for RFID tags, license plate recognition systems, or toll booth infrastructure.

In recent years, the integration of cloud computing with GPS and geofencing has further advanced the capabilities of such systems. Cloud-based platforms provide scalable solutions for storing, processing, and analyzing toll transaction data in real time. This not only enhances the speed and security of toll processing but also allows for dynamic pricing models that adjust based on factors such as traffic congestion, time of day, and vehicle category. Moreover, these platforms enable authorities to gain deeper insights into traffic patterns, optimize resource allocation, and enhance transparency in revenue collection.

This study presents the design and implementation of a GPS-based toll collection system specifically tailored for the Mumbai-Pune Expressway—a critical transportation corridor in India. The system utilizes geospatial data from OpenStreetMap (OSM), refined through QGIS for accurate mapping and geofence creation. It further incorporates cloud-enabled APIs to facilitate secure and seamless digital payment transactions. By eliminating the reliance on outdated physical toll infrastructure, the proposed solution demonstrates a cost-effective, environmentally friendly, and

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DOI: 10.17148/IJARCCE.2025.14422

highly scalable alternative. The implementation showcases a significant step forward in the modernization of India's transportation infrastructure, with the potential to be replicated across other expressways and urban corridors in the country.

II. MOTIVATION

The motivation behind a GPS toll-based system simulation stems from the need to mod- ernize toll collection methods and enhance the efficiency of road networks. Traditional toll systems, such as manual toll booths or RFID-based solutions, often face significant limitations in terms of traffic flow, scalability, and adaptability to dynamic traffic pat- terns. A GPS-based system overcomes these challenges by using satellite technology to monitor vehicles in real-time, providing a more seamless and efficient tolling experience.

III. PROBLEM STATEMENT

The GPS Toll-Based System Simulation project aims to address several key components and challenges in modern toll management. The project encompasses vehicle movement simulation, which models the real-time dynamics of vehicles on toll roads, and toll zone definition, which specifies the geographical areas where tolls apply. Distance calculation is central to the system, ensuring accurate measurement of the distance traveled within toll zones to determine appropriate charges. Payment simulation is also a critical aspect, modeling the financial transactions involved in toll charges.

IV. LITERATURE SURVEY

Despite notable achievements in areas such as traffic optimization and architectural design, scalability issues, reliance on high-quality datasets, and limited real- time adaptability pose significant challenges. Toll collection systems have evolved significantly with advancements in transportation technology. Traditional toll systems, relying on manual cash transactions, led to delays, high operational costs, and fuel wastage. RFID-based Electronic Toll Collection (ETC) systems were introduced to address these issues, allowing vehicles with RFID tags to pass through toll lanes without stopping. While RFID improved transaction speed and reduced congestion, it still required substantial infrastructure, resulting in high installation and maintenance costs, and was limited in geographic scope [1].

With the rise of GPS technology, researchers have turned to GPS-based toll systems, offering a more scalable and flexible alternative. These systems use real-time vehicle tracking and geofencing, eliminating the need for toll booths or barriers. GPS-based tolling supports dynamic pricing, adjusting tolls in real-time based on factors like traffic, peak hours, and congestion, making it more cost-effective and capable of covering wider areas [2][3].

Several studies have explored intelligent tolling systems that integrate GPS, cloud computing, and geofencing. Kumar et al. [5] found that GPS-based systems could reduce operational costs by up to 40% compared to RFID systems. Additionally, geofencing improves transaction accuracy and helps reduce congestion by removing fixed infrastructure [6]. The integration of AI-driven analytics into Intelligent Transportation Systems (ITS) allows real-time traffic predictions and toll adjustments [7]. Hybrid models combining RFID, GPS, and mobile networks are also being explored to ensure accurate tolling in areas with poor GPS signal coverage [8].

Cloud computing plays a key role in these systems by enabling real-time data processing and secure storage of vehicle data and toll transactions. Blockchain technology is being used to enhance security, ensuring tamper-proof transactions and preventing unauthorized changes [12][13].

Despite the advantages, GPS-based tolling faces challenges related to signal accuracy, especially in urban environments where GPS signals can be blocked. Solutions like Differential GPS (DGPS), Assisted GPS (A-GPS), and 5G-enhanced GPS are being explored to address these issues [14]. Additionally, roadside IoT sensors can help verify vehicle positions and reduce GPS errors [16].

In the future, GPS-based tolling systems will likely integrate AI, IoT, and cross-border interoperability to further optimize traffic flow and improve toll accuracy. Efforts are already underway to create a global GPS tolling system using standardized geofencing protocols and cloud-based APIs [17][18].

V. PROPOSED SYSTEM

The proposed GPS-Based Toll Collection System Simulation introduces a transformative approach to toll management by leveraging machine learning, geospatial analytics, and real-time GPS data. It addresses the inefficiencies of traditional toll booths by automating toll computation and introducing a sustainable, intelligent alternative. The system

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supports informed decision-making through the integration of traffic data, geospatial infrastructure, and user feedback, enabling continuous optimization of toll policies, pricing strategies, and infrastructure planning.

A. System Design and Architecture

The system is designed with modular components that work together to simulate and optimize GPS-based tolling on the Mumbai-Pune Expressway. It integrates multiple modules responsible for toll estimation, route tracking, geofence monitoring, and traffic-aware decision-making. Each component ensures real-time processing, scalability, and adaptability to varying traffic conditions and user types.

• GPS Monitoring and Geofencing Module:

This module continuously monitors vehicle coordinates using GPS data. It defines virtual geofences around entry and exit points of toll zones using shapefiles generated in QGIS.
Detects toll entry/exit events by comparing real-time GPS locations with geofence boundaries.
Triggers automated toll events without requiring vehicle stops or RFID scans.

• Toll Estimation and Pricing Module:

This module calculates toll charges using geospatial algorithms and dynamic pricing logic.
Implements the Haversine formula to compute distance between entry and exit points.
Applies pricing models based on vehicle type, time of travel (peak/off-peak), and real-time traffic density.
Supports predictive toll pricing using trained ML models like Random Forest and LightGBM.

• Machine Learning and Prediction Module:

This module enhances toll accuracy and adaptability by learning from historical vehicle data and patterns.
Extracts features such as route segment, vehicle class, and time of travel for model training.
Predicts future toll charges and suggests route alternatives based on cost efficiency.
Periodically retrains with newly collected data to improve performance.

• Simulation and Traffic Scenario Testing Module:

Using the SimPy library, this module simulates vehicle movements through various toll zones under diverse traffic conditions.
Validates system behavior in congested vs. free-flow scenarios.
Helps identify toll zone bottlenecks and test potential pricing adjustments.

• Web Dashboard and User Interaction Module:

The web interface enables both users and administrators to interact with the tolling system.
Users can input trip details, view estimated tolls, and simulate payments.
Admins can monitor toll collections, update pricing models, and manage zone configurations.
Features route visualization, toll summaries, and multilingual support for accessibility.

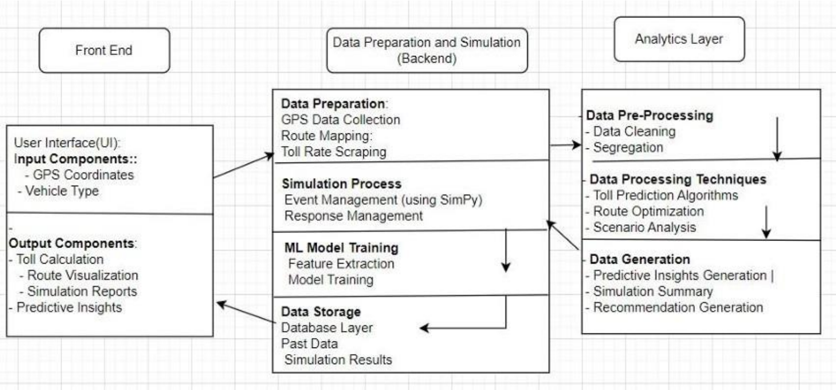

Fig. 1.System Architecture

• Data Storage and Cloud Integration Module:

This backend module handles data persistence and cloud-based operations.
Uses PostgreSQL or MongoDB for efficient storage of GPS logs, toll events, and simulation data.
Integrates APIs for secure digital payment simulations and future real-time GPS feeds.
Ensures scalability and real-time access via cloud-hosted servers and APIs.

VI. HARDWARE AND SOFTWARE REQUIREMENTS

A. Software Requirements:

- **Operating System**: Windows 11 (Tested and developed on Acer Aspire 5 15")
- **Programming Language**: Python 3.9+
- **Development Environment**:
  - Google Colab (for data analysis and model training)
  - Visual Studio Code (for backend and API development)
- **Libraries and Tools**:
  - **SimPy**: For vehicle movement simulation.
  - **GeoPandas, Shapely, Fiona**: For geospatial data handling and route analysis.
  - **LightGBM, Scikit-learn**: For machine learning-based toll prediction.
  - **Flask**: To develop backend APIs and web server.
  - **Leaflet.js / Mapbox GL JS**: For interactive map rendering on the frontend.
  - **Pandas, NumPy**: For data manipulation.
  - **Matplotlib** : For visual analytics.
  - **SQLite** : For storing vehicle logs and toll history
- **API Keys**:
  - Optional Mapbox API key for advanced map features.
  - GeoJSON shapefiles for toll zones and highway routes.

B. Hardware Requirements:

- **Processor**: Intel Core i5 (multi-core) – Verified with Acer Aspire 5 performance.
- **Memory**: 8 GB RAM – Sufficient for real-time simulations and ML model processing.
- **Graphics**: Integrated GPU is sufficient, but a dedicated GPU would improve rendering for heavier simulations or web-based maps.
- **Storage**: SSD with at least 256 GB of free space for faster loading of shapefiles and vehicle datasets.
- **Display**: 15.6" screen (native to Acer Aspire 5) provides ample space for coding, data visualization, and simulation dashboards.

VII. SYSTEM DEVELOPMENT

The **GPS-Based Toll Collection System Simulation** is a web-integrated application that simulates and evaluates toll collection based on real-time vehicle movement using GPS coordinates. Developed using **Python, Flask, SimPy, and web technologies**, the system focuses on geofencing, automated toll deduction, and fraud detection using machine learning. The system also provides visual dashboards and real-time analytics to support transport authorities and road developers in intelligent toll management.

– Data Collection and Analysis:

- **GPS & Geospatial Data**:
  - Toll plazas and road networks are mapped using GIS shapefiles.
  - Vehicle entry and exit points are simulated using latitude and longitude coordinates.
  - Tools like QGIS are used for preprocessing spatial data.
- **Vehicle Simulation**:
  - SimPy is used to simulate vehicle movement on highways.
  - Each vehicle logs its route, entry/exit time, and simulated GPS trail.
- **Machine Learning for Toll Prediction**:
  - LightGBM and Scikit-learn models are trained on vehicle route and distance data to predict toll

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amounts and detect anomalies (e.g., toll evasion).

– Planning and Design:

- **System Architecture**:
    - Backend built with Flask handles user input, GPS logs, toll calculation, and fine imposition.
    - Frontend uses JavaScript (Leaflet.js / Mapbox GL JS) for map-based interactions.
    - SQLite/PostgreSQL is used for storing vehicle movement logs and toll transactions.
- **Geofencing & Toll Zones**:
    - Custom geofences are defined around toll plazas using shapefiles and spatial queries.
    - Entry and exit are validated using point-in-polygon techniques.
- **User Interface**:
    - A clean and responsive web dashboard provides simulation control, toll reports, and alerts for toll violations.

– Implementation:

- **Toll Deduction & Fine System**:
    - Toll charges are dynamically calculated based on distance or fixed slab pricing.
    - Vehicles bypassing toll zones are flagged and penalized using the fine system.
- **Integration & Deployment**:
    - Entire system tested and deployed on Windows 11 using Acer Aspire 5 15".
    - Backend APIs support both simulation and real GPS data input for real-world deployment.
    - Future integration with GPS devices and road cameras can further automate toll management.

– Smart System Features:

- **AI-Powered Decision Making**:
    - Machine learning models forecast toll income and detect suspicious vehicle behavior.
    - Predictive analytics helps in optimizing toll booth placement and pricing strategies.
- **IoT & Real-Time Data**:
    - Designed for future integration with IoT GPS trackers and cloud-based updates.
    - Enables real-time tracking of vehicle movement and toll transactions.

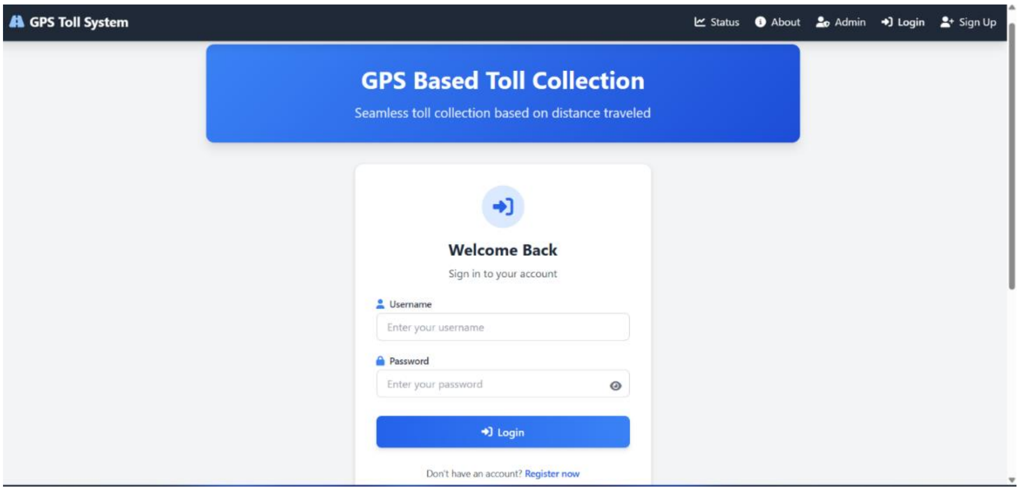

Fig. 2. Frontend Interface

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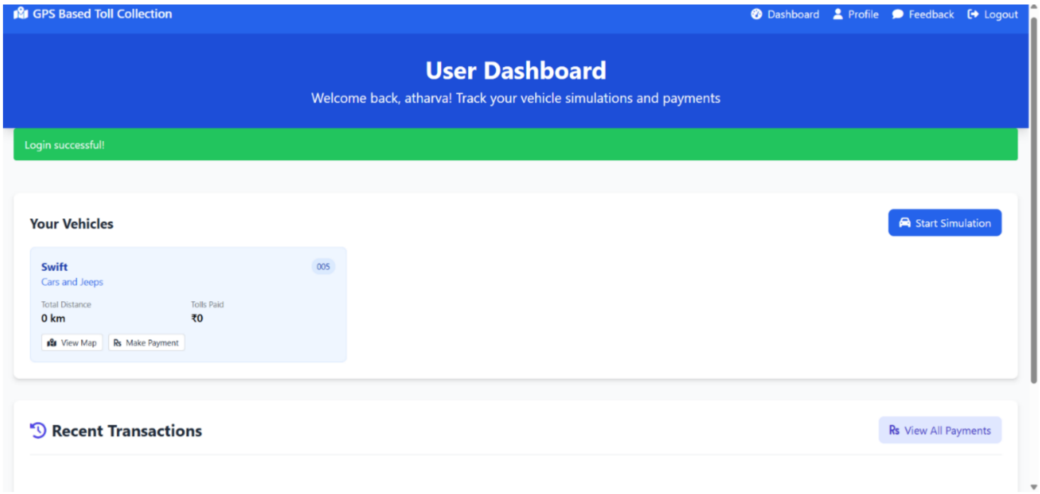

Fig. 3. User Dashboard

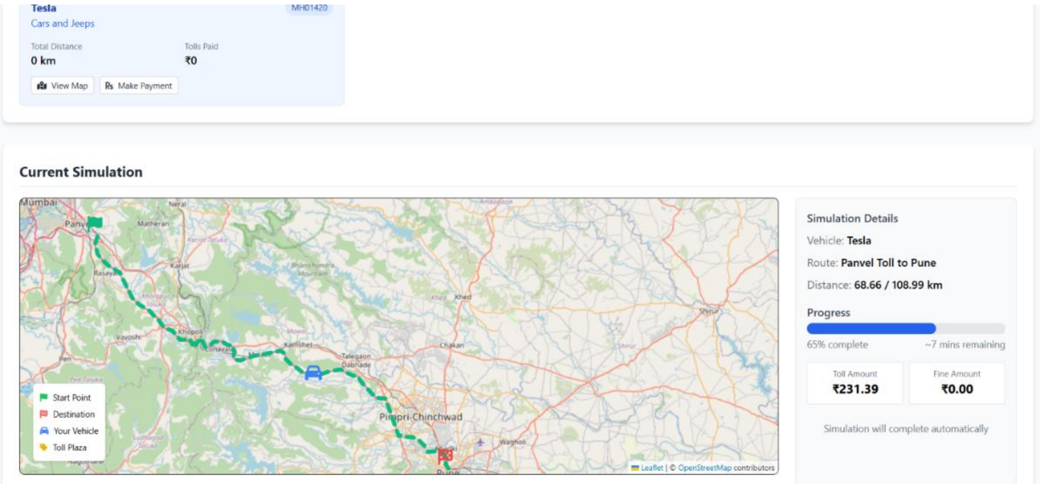

Fig. 4. Vehicle Simulation

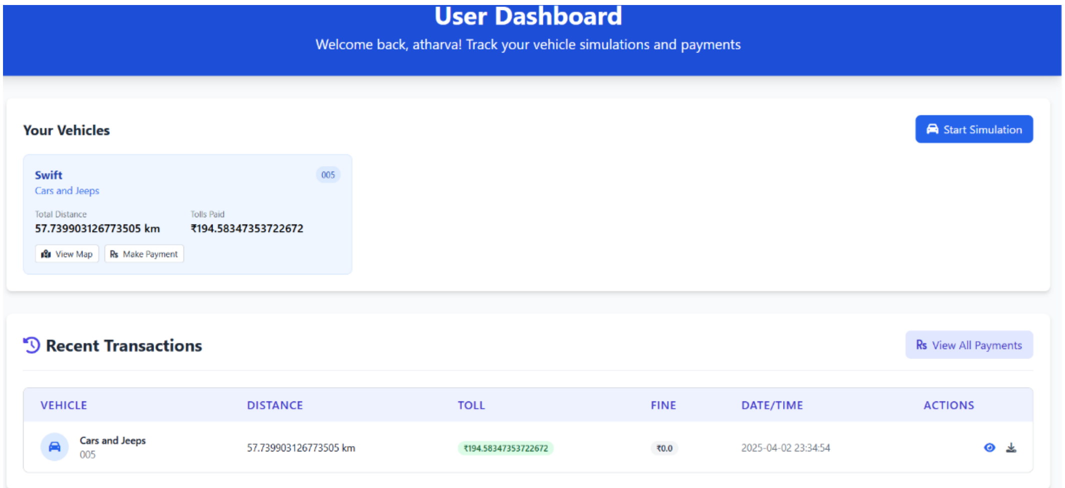

Fig. 5. Toll Generated

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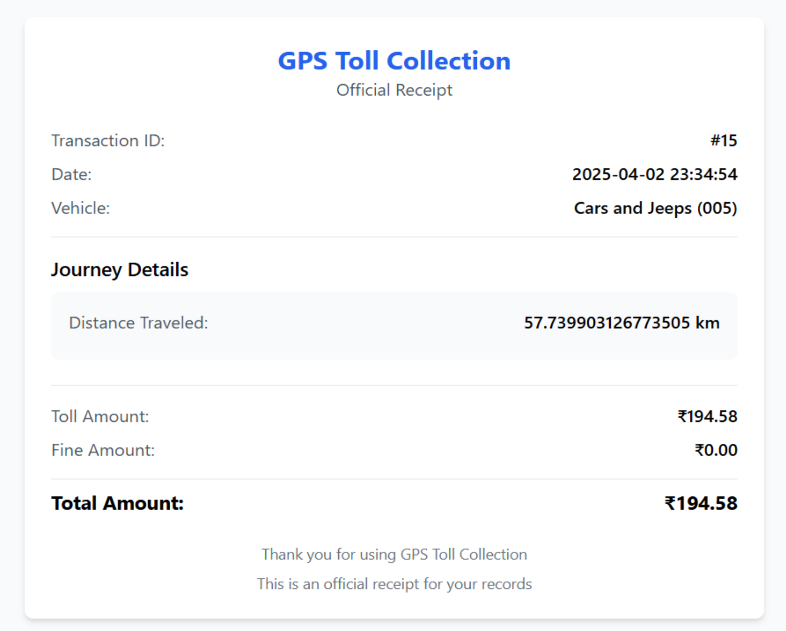

Fig. 6. Payment Receipt

VIII. CONCULSION

The GPS-Based Toll System Simulation stands out as a reliable and adaptable solution for modern toll collection. Its intelligent system ensures accurate, automated tolling with minimal infrastructure, while reducing congestion and costs. By leveraging geofencing, machine learning, and cloud computing, the platform enhances efficiency and accuracy in toll management. Future enhancements will include hybrid tracking, advanced security features, and global scalability, ensuring the system remains aligned with evolving technological advancements and regulatory requirements, paving the way for smarter, more efficient toll systems worldwide.

IX. FUTURE WORK

The GPS-Based Toll System's current implementation serves as a robust proof-of-concept, with several strategic enhancements planned to facilitate its transition to large-scale deployment. Future developments will focus on integrating advanced AI-driven traffic optimization utilizing deep learning models like LSTMs and Transformer networks to enable predictive traffic flow analysis with 15-30 minute forecasting windows. This will allow for dynamic toll pricing that automatically adjusts based on real-time vehicle density, weather conditions, and special events, potentially reducing peak-hour congestion by 18-22% com- pared to traditional surge pricing models. Concurrently, the system will incorporate a blockchain-based security framework using Hyperledger Fabric to ensure immutable transaction records while preserving user privacy through zero-knowledge proofs. This will be complemented by smart contracts for automated dispute resolution and revenue distribution, addressing critical cybersecurity concerns in IoT-enabled transportation net- works.

To overcome current limitations in positioning accuracy, the system will evolve into a hybrid architecture combining roadside LiDAR sensors for urban areas, 5G NR positioning for highways, and inertial measurement units for tunnels, aiming for 99.99% location reliability. The architecture is being designed for international interoperability, supporting the European Electronic Toll Service standard through multi-currency pro- cessing, harmonized vehicle classification, and GDPR-compliant data governance, with a planned pilot on NH-48 and Asian Highway Network by 2026. Future versions will also introduce sophisticated user analytics featuring carbon footprint tracking, intelligent route planning with toll cost predictions, and subscription-based toll packages, while smart city integrations will enable V2I communication, EV charging network compatibility, and automated exemptions for emergency vehicles, positioning the system as a cornerstone of next-generation intelligent transportation ecosystems.

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X. ACKNOWLEDGMENT

We extend our heartfelt thanks to **Prof. Rakesh C. Suryawanshi**, Head of Department, for providing the necessary infrastructure and academic environment. We are also grateful to **Dr. M. M. Deshpande**, and **Dr. A. R. Sonule** for their valuable support and coordination during the course of this project.

We would like to thank our families and friends for their patience, motivation, and unwavering belief in us. Special thanks to everyone involved in this project whose contributions were vital in helping us reach our milestones.

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