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Design and Implementation of an Automated Toll Collection System

Moses Kwasi Torkudzor ^{*} , Stephen Andoh Baffoe , Gabriel Senyah , Micheal Gyamfi Opoku , Yitzak Ofori , Patrick Atsu Agbemabiese 

Department of Electrical and Electronic Engineering, Koforidua Technical University, Koforidua P.O. Box KF 981, Ghana

ABSTRACT

Manual toll collection systems exacerbate traffic congestion, economic inefficiency, and environmental pollution, particularly in rapidly urbanizing regions. Several technologies were introduced over the years to address problems associated with manual toll collection. Despite these developments, challenges remain in making the toll collection system more efficient. This study therefore presents the design, construction, and validation of a fully functional prototype of an Automated Toll Collection System (ATCS) to address traffic congestion and its associated issues. The system integrates an ESP32 microcontroller, an MFRC522 Radio Frequency Identification (RFID) reader for vehicle identification, and a load cell with an HX711 amplifier for Weight-In-Motion (WIM) measurement. A dynamic toll calculation algorithm implements a fair, weight-based pricing model which provides a practical solution for addressing the issues of vehicular traffic congestion associated with the traditional manual system of toll collection. Firebase, together with a custom Node.js webhook, has been integrated with the Paystack payment system Application Programming Interface (API) to process real-time mobile money toll payment/top-ups, and If This Then That (IFTTT) services are used for transaction logging and user notifications. Validation demonstrates the prototype's robust functionality by successfully processing transactions with sufficient balances and intelligently handling insufficient funds by recording debt and automatically generating payment links. By enabling non-stop vehicular flow, cashless

*CORRESPONDING AUTHOR:

Moses Kwasi Torkudzor, Department of Electrical and Electronic Engineering, Koforidua Technical University, Koforidua P.O. Box KF 981, Ghana; Email: moses.torkudzor@ktu.edu.gh

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transactions, and equitable data-driven tolling, this scalable IoT-based solution is applicable in transportation infrastructure, enhancing traffic flow, revenue security, and sustainable urban mobility.

Keywords: Automated Toll Collection; Internet of Things (IoT); Radio Frequency Identification; Weigh-In-Motion; Cashless Payment; Smart Transportation

1. Introduction

Urbanization and population growth have placed significant strain on transportation infrastructure worldwide, highlighting the critical need for efficient traffic management systems. In many countries, including Ghana, reliance on manual toll collection has become a major bottleneck, leading to persistent traffic congestion, economic losses, environmental harm, and security vulnerabilities^[1,2]. The state of vehicular traffic congestion wastes travel time, increases fuel consumption and gas emissions; such situations are extremely troubling and affect the advancement of a country^[3,4]. These challenges underscore an urgent need to improve tolling systems through automation and smart technology.

Current research in intelligent transportation systems (ITS) proposes solutions by leveraging the Internet of Things (IoT), RFID, and seamless digital payment gateways to create cashless, free-flow tolling^[5,6]. While automated systems exist, many lack integration with equitable, weight-based charging models or real-time financial reconciliation^[7,8]. This gap presents an opportunity to design a more holistic system that addresses identification and payment by taking the weight of vehicles into consideration for transparency and scalability.

Among the various technologies that exist in automatic vehicle toll collection systems, camera-based systems, also known as Automatic Number Plate Recognition (ANPR), and RFID techniques have emerged as the most popular. To ensure fairness in computing the toll and efficient traffic management, the WIM sensor approach is combined with either of these two methods or both^[9,10].

A WIM sensor comprises a quartz crystal that is responsive to the strain induced by a vehicle's weight. When installed, it captures the vehicle's dynamic weight as it passes over, which is used to determine the appropriate toll fee. The WIM sensor approach is applied in Srikanth and Poornima^[11] with camera as the vehicle recognition device

instead of the RFID technique. According to the authors, the proposal in Srikanth and Poornima^[11] can be integrated into an existing ATCS system known as the FASTag to ensure fair tolling and automatic vehicle identification, thereby enhancing its performance. FASTag is a technology designed and implemented in India that uses an RFID-based device attached to a vehicle's windshield that enables automatic toll payment by allowing RFID readers at toll booths to identify the vehicle and deduct the toll amount from the linked account, thereby reducing manual cash transactions, traffic congestion, travel time, and fuel consumption^[2,11]. Although FASTag improves electronic toll collection efficiency, the system still relies on physical toll plazas where vehicles must slow down or stop for card validation, which can contribute to traffic congestion during peak hours^[12]. If a FASTag account has insufficient balance, the tag may be blacklisted, and the toll transaction can be declined, which is likely to attract a penalty from the users^[13]. This means that account balance and debt management are not efficiently integrated into the FASTag tolling system.

Compared to the camera-based technology, the RFID has several advantages, including effectiveness, low cost, and faster processing^[14], lower cost, improved security measures, accuracy, efficiency, and improved scalability^[15]. In outstanding high speeds as well as longer lifetime, RFID technology is immune to environmental conditions including snow, dirt, sun ray, or vehicle headlight glare, license plates with red-coloured numbers, which reduce its detection rate performance^[16]. In addition, the research by Raad and Sheltami^[17] illustrates that RFID-based automatic toll systems utilise considerably less energy than camera-based systems, as RFID depends on passive or low-power tag-reader communication, while camera technologies necessitate continuous image capture, illumination, and resource-intensive image processing. RFID technology has demonstrated efficacy in addressing various tracking and localisation challenges prevalent in image processing systems, and comparably provides speed detection tracking

of vehicles irrespective of their location, and the highest accuracy rates for vehicle recognition because it employs a radio frequency technique ^[18]. Recently, Alam et al. ^[10] proposed a solar-powered ATCS that integrates RFID technology with a weight sensor to identify vehicles and determine toll charges based on the vehicle's weight. The RFID reader retrieves vehicle information from a database while the weight sensor measures the load to classify the vehicle. The use of solar energy improves system sustainability and reduces operational costs, while experimental results show reduced waiting time and improved toll accuracy. However, the system may face scalability challenges in high-traffic environments since it was designed as a small-scale prototype. Research by de Coning et al. ^[19] focused on improving freight corridor monitoring through a joint intelligent WIM system and machine learning algorithms to detect overloaded vehicles. The system improves vehicle screening efficiency and reduces the need for static inspections, thereby enhancing traffic flow. However, its primary focus on freight monitoring rather than toll collection limits its direct application in general electronic toll collection systems. In a related study, Soma et al. ^[20] proposed an ATCS using RFID technology and cloud connectivity. In this system, RFID readers installed at toll gates detect vehicle tags and communicate with a cloud server that stores user account information. The toll fee is automatically deducted from the user's account, and the transaction details are stored in the cloud for monitoring and analysis. The use of IoT enables real-time data management and remote monitoring. The system significantly reduces manual intervention time and processing time compared with conventional toll booths. Nevertheless, the system does not incorporate vehicle weight measurement or advanced vehicle classification techniques, which limits its ability to implement dynamic toll pricing based on vehicle load.

Machine learning is another technique currently receiving high interest in the research community as a promising approach to addressing the problem of automated toll collection. In Teja et al. ^[21], an ATCS that integrates RFID technology with deep learning-based vehicle classification using a convolutional neural network model is presented. The RFID identifies vehicles while camera-based image analysis verifies vehicle types to prevent tag misuse or swapping. The approach improves toll accuracy and sys-

tem security but requires additional camera infrastructure and substantial computational resources, thereby increasing deployment and maintenance costs. In another study ^[22], a modular multisensory WIM was proposed that uses a transformer-gated recurrent unit neural network for axle recognition and vehicle weight estimation at highway speeds. One major advantage of this system is its ability to perform accurate measurements under varying traffic speeds. The complex multi-sensor architecture and machine learning algorithms, however, may increase installation costs and maintenance requirements.

The existing literature revealed that the majority of the work done in smart vehicle toll pricing lacks the integration of dynamic vehicle weight identification for a dynamic pricing mechanism. Most implementations use the well-established RFID-based identification in combination with pre-defined, static vehicle classes for toll calculation. This work, therefore, presents the design and prototype implementation of an ATCS that integrates Ultra High Frequency (UHF) RFID for vehicle identification, a load cell for WIM measurement, and a cloud-based financial engine using Firebase and the Paystack API. The system aims to enable seamless, cashless transactions while introducing a dynamic, weight-based pricing structure to promote equity. Furthermore, it incorporates real-time notifications and debt management to enhance usability and accountability.

The contributions in this research work are summarized as follows:

- Unique integration of Firebase for real-time database management, Node.js backend services hosted on Render platform to integrate Paystack for secure payment processing, and IFTTT webhooks for SMS notifications into a unified event-driven framework.
- A mathematical model is proposed which incorporates the deduction of the weight of the load cell mounting assembly to ensure toll fees reflect net vehicle weight, thereby ensuring fairness and accuracy in toll collection.
- Dynamic debt-aware top-up algorithm enables the system to automatically create an end-to-end debt management scheme absent from existing electronic toll collection techniques.

The rest of the paper is organized as follows: Section

2 elaborates on the system’s design and methodology, detailing the architecture encompassing both hardware components and software elements. In Section 3, a detailed discussion of the experimental results and performance analysis is presented. Finally, the fourth Section concludes the report.

2. Materials and Methods

The system was designed and validated through the development of a functional prototype, integrating hardware components, a cloud-based software architecture that includes Node.js, Render Server, Firebase, Paystack, and IFTTT webhook, and a defined operational algorithm. Sufficient detail is provided to allow for replication.

2.1. System Architecture and Design

As shown in **Figure 1**, the system comprises three interconnected layers: a physical sensing and control unit,

a cloud-based data and payment service, and a user notification module. The core hardware controller is an ESP32-WROOM-32 microcontroller. Vehicle identification is achieved using an MFRC522 RFID reader module (13.56 MHz) scanning passive RFID tags, each with a unique identifier (UID). The MFRC522 RFID module offers security features for contactless identification and access management, mostly based on the ISO/IEC 14443A standard [23,24]. The CRYPTO1 encryption technique, which enables safe communication between an RFID card and a reader, is one of this standard’s main features. For weight-in-motion measurement, a 20 kg capacity load cell with an HX711 amplifier module was embedded into the model roadway. Visual feedback was provided through a multi-color LED array (red, green, blue, yellow) connected to the ESP32 via a Vero board with appropriate current-limiting resistors. The prototype structure was constructed from high-density foam board, with the electronics housed within a scaled toll booth model. The system was powered by a rechargeable Li-Po battery via a dedicated charging circuit.

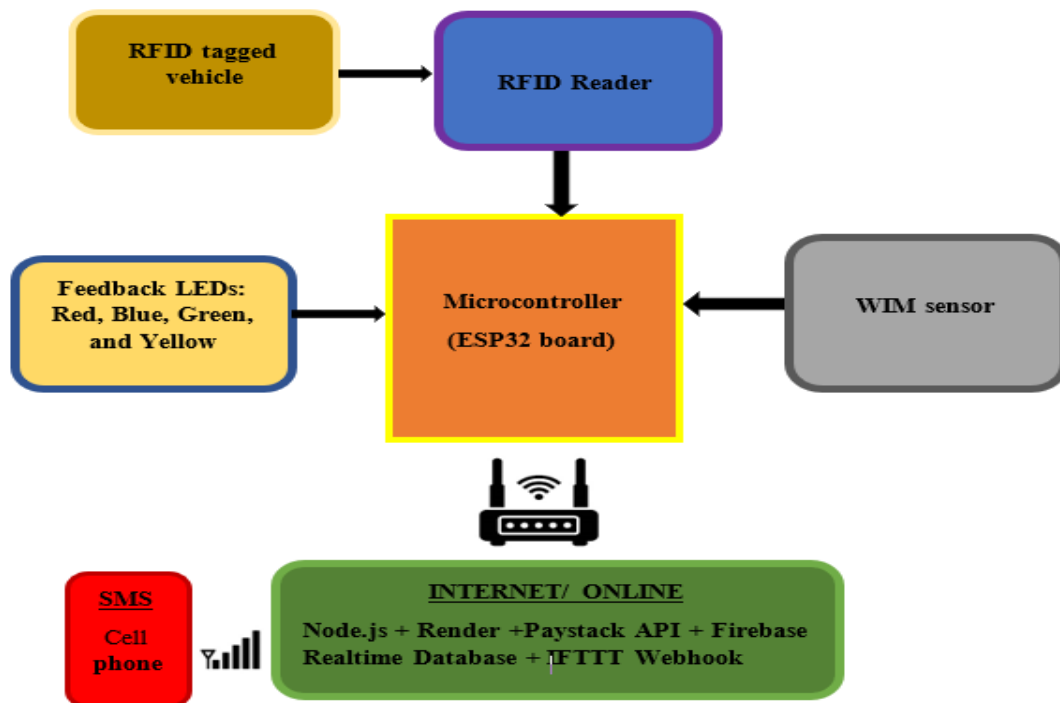


Figure 1. Block diagram of the ATCS illustrating the integration of its various components.

The cloud backend utilized Google Firebase Realtime Database to maintain user accounts, linking each RFID UID to a digital wallet balance and transaction his-

tory. To protect financial transactions from software-based threats, Firebase provides built-in security by adhering to stringent global privacy laws such as the General Data Pro-

tection Regulation (GDPR), California Consumer Privacy Act (CCPA), and California Privacy Rights Act (CPRA), where Google acts as a data processor on behalf of the customer [25]. Additionally, all Firebase services are independently certified under major security standards, including ISO 27001 and SOC 1, 2, and 3, with some services meeting the enhanced cloud-specific standards of ISO 27017 and ISO 27018, ensuring a verified and compliant foundation for handling sensitive financial data [25]. A custom Node.js server, deployed on the Render platform, acted as a webhook to integrate the live Paystack API for processing real-money top-ups via mobile money or card. The “If This Then That” (IFTTT) service was configured with Webhooks to send email notifications for transaction

events and to log all transactions automatically to a Google Sheets spreadsheet for administrative audit trails.

The ATCS is built on an integrated hardware circuit centered on an ESP32 microcontroller, as shown in **Figure 2**. The design seamlessly connects three key subsystems: an MFRC522 RFID reader for vehicle identification via SPI communication (using pins like GPIO 5, 18, and 19), a load cell with an HX711 amplifier in a Wheatstone bridge configuration for precise weight measurement (connected via GPIO 32 and 33), and a multi-color LED array on GPIO pins 25, 26, 27, and 14 for visual user feedback. Each component was strategically selected and virtually modeled using Circuit Designer software to ensure real-world compatibility before physical assembly.

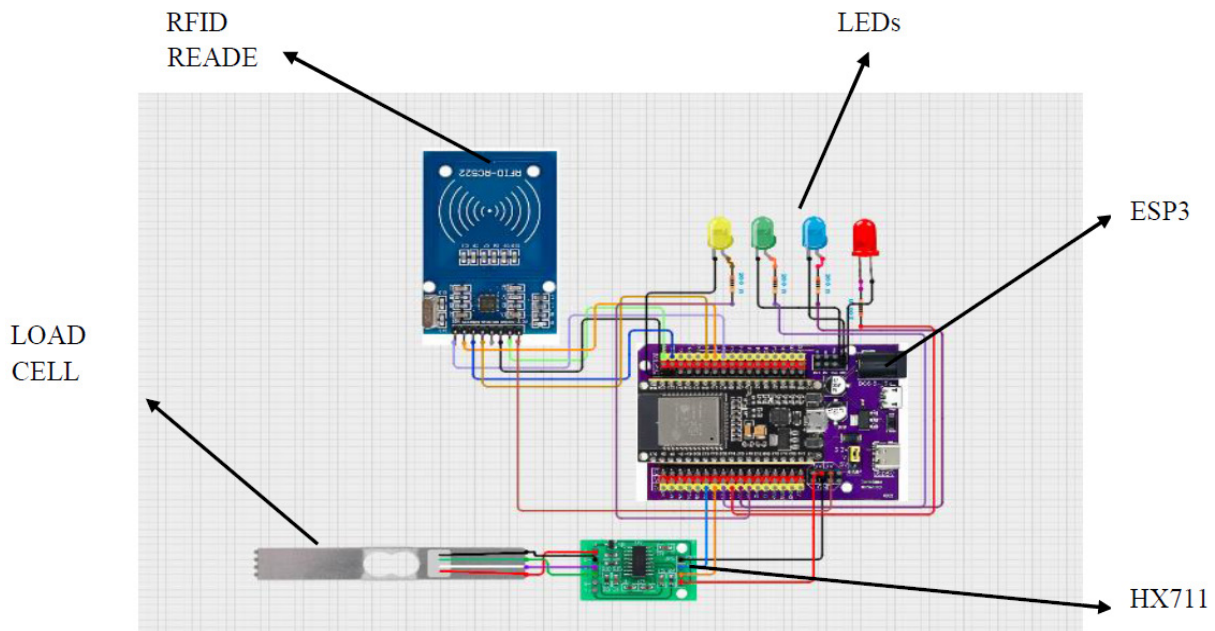


Figure 2. Circuit Diagram of the Automated Toll Collection System.

This virtual design was then translated directly into a physical prototype as shown in **Figure 2**, with every connection adhering to the validated pin mappings. Testing confirmed the system’s robust functionality, demonstrating accurate RFID tag reading, reliable weight data transmission, and appropriate LED indicators for operational status. The result is a fully operational circuit that forms a reliable hardware foundation for the automated toll collection process, ensuring all components communicate effectively to execute the intended workflow.

The ATCS operates on a sequential, automated work-

flow as shown in **Figure 3**. The process initiates as a vehicle approaches a toll collection point and its RFID tag is scanned for identification. The vehicle’s weight is then measured by a weigh-in-motion sensor. This data is used to calculate the appropriate toll fee using Equation (1). The system then checks the linked account balance. If sufficient, the toll is deducted automatically; if not, the amount is recorded as a debt to maintain traffic flow. Finally, the transaction details are logged into a central database, and a notification is sent to the user. The system then resets, ready for the next vehicle, enabling seamless and cashless tolling.

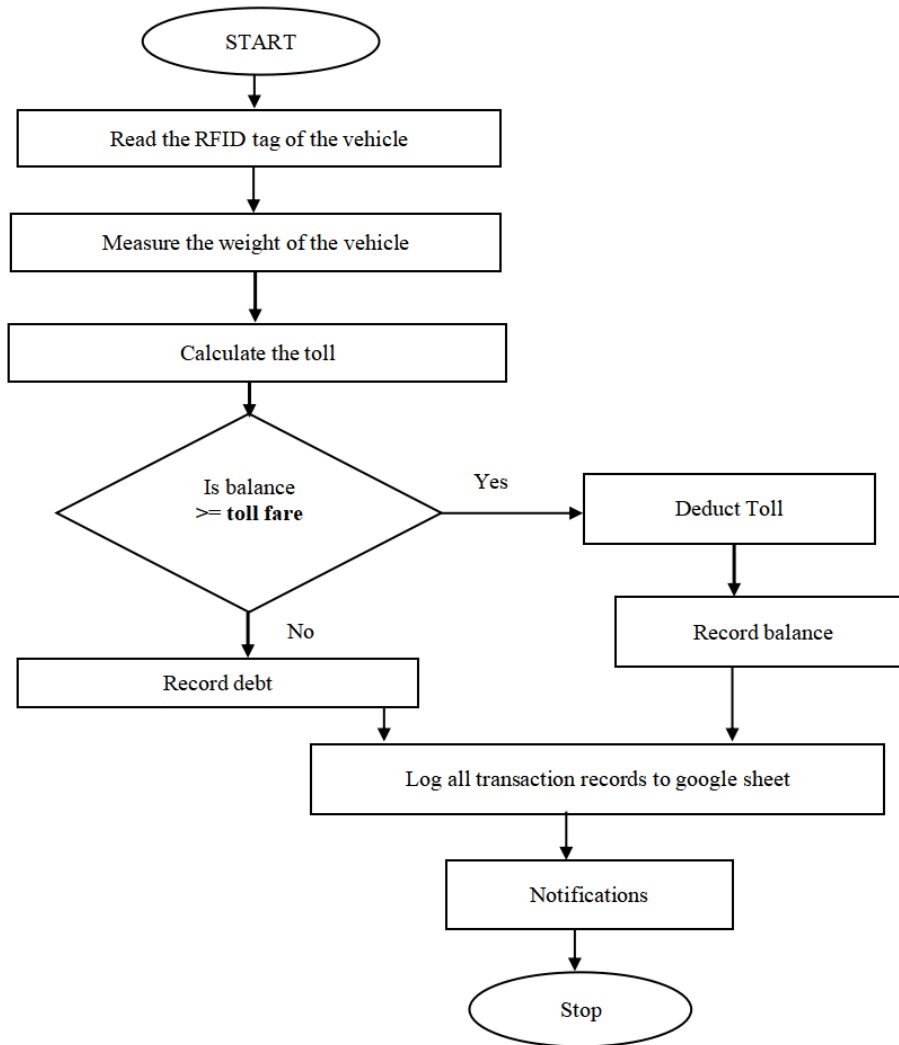


Figure 3. Flow chart of the automated toll collection system.

2.2. Operational Algorithm and Mathematical Models

The system operates according to a sequential logic. Upon detecting an RFID tag, the system captures the vehicle’s weight using the load cell, applies a debounce period to ignore duplicate reads, and processes the vehicle in a first-in, first-out queue.

2.2.1. Toll Calculation Model

The determination of the toll fee is governed by the mathematical model formulated and presented in Equation (1).

$$T = \frac{c}{W}(v - k) \quad (1)$$

In this equation, T , v , k , c , and W respectively represent the toll fee, the measured gross weight of the ve-

hicle, the weight of the load cell mounting assembly, the base fare pay unit, and the minimum weight unit. From the equation, k is a constant weight of 1.8 kg subtracted from the measured gross weight to fairly determine the net weight of the vehicle and its load. The minimum weight unit parameter, W , has a design value of 5.0 kg, which establishes the weight variation that forms the basis of the toll calculation. The parameter c forms the base fare per unit weight set at a design value of GH¢3.00. This value represents the monetary charge applied for each unit of weight (W).

2.2.2. Top-Up Calculation and Debt Management

In the ATCS, the possibility of insufficient wallet balance must be addressed through a dedicated and auto-

mated logic. When a user’s wallet balance falls below the calculated toll fee for a given passage, the system initiates a structured debt management protocol designed to resolve the shortfall efficiently while maintaining user convenience.

Upon detecting that the available balance is less than the required toll amount T , the system automatically records the outstanding amount as a debt, denoted by D , in the user’s Firebase profile. This ensures that the financial obligation is formally documented and associated with the user’s account for subsequent resolution. Simultaneously, the system triggers a notification to alert the user of the insufficient balance and the incurred debt, promoting transparency and immediate awareness of the account status. To facilitate the swift resolution of the debt, the system employs a mathematical model that calculates a recommended top-up amount, T_u , which is presented in Equation (2).

$$T_u = \max(m, D + T + q) \quad (2)$$

The outstanding debt D (GH¢) represents the amount already owed by the user from a failed transaction. The current toll, T (GH¢) is the fee for the passage that triggers an insufficient balance, ensuring that the top-up covers both the existing debt and the immediate charge. A buffer amount, denoted by q with a design value of GH¢2.00, is added to prevent the account from immediately returning to a low balance state after deductions are applied. The

minimum transaction threshold, m , with a design value of GH¢5.00, establishes a base for any top-up transaction. The expression in Equation (2) therefore compares this minimum threshold against the sum of debt, current toll, and buffer value, setting the recommended top-up amount. Once the recommended top-up amount T_u has been determined, the system automatically generates a personalized Paystack payment link for the amount T_u and sends it to the user via email. Upon successful payment confirmation via the webhook, the debt D is cleared, the toll T is deducted, and the remaining funds are credited to the user’s wallet in the Firebase.

2.3. Prototype Construction and Integration

The physical prototype presented in **Figure 4** was constructed to enable realistic testing. As shown in the figure, a toll booth and roadway were fabricated from high-density foam board. The load cell was recessed into the roadway surface to allow model vehicles to pass over it. The RFID reader was mounted on the roadside. All electronic components were housed within the foam structure and connected to the EP32 on a breadboard. Firmware for the ESP32 was written in C/C++ using the Arduino IDE, managing sensor input, cloud communication via WiFi, and LED state control.

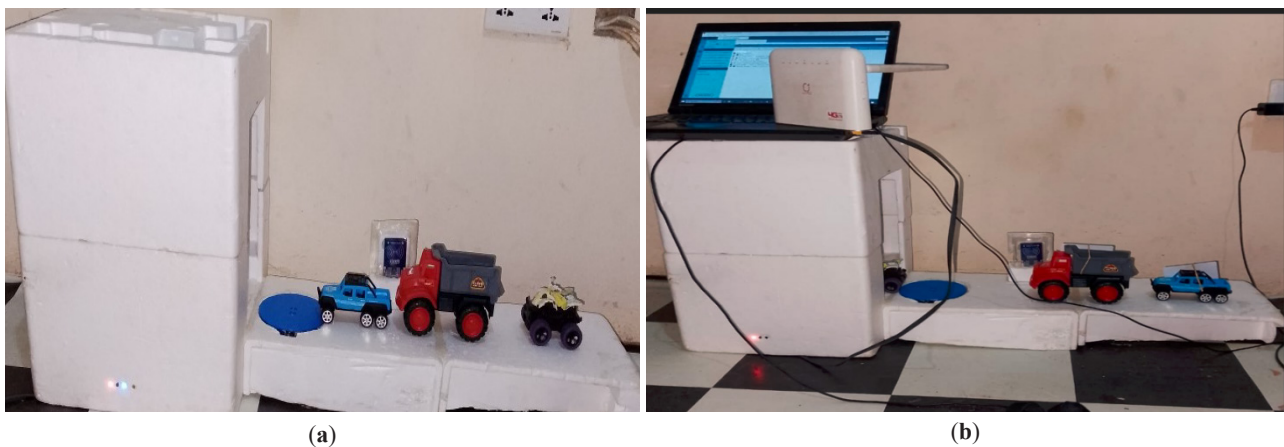


Figure 4. (a) Constructed prototype showing the architecture of the ATCS. (b) Real-time performance testing of the ATCS.

2.4. Validation and Testing of the System

The system’s functionality was validated through a

structured series of tests monitored via the Arduino IDE Serial Monitor. Component-level testing verified RFID reading accuracy, load cell calibration, and LED signaling.

End-to-end validation simulated three core scenarios:

1. **Successful Transaction:** Vehicles with sufficient wallet balance were processed. The system correctly identified the RFID, measured a vehicle’s weight, calculated the toll based on the weight measured, deducted the fee from Firebase, and triggered confirmation emails and spreadsheet logging.
2. **Insufficient Balance & Debt Recording:** Vehicles with a balance lower than the toll were presented. The system correctly aborted the payment, recorded the debt in Firebase, and dispatched an email alert with a top-up link.
3. **Debt Clearance:** Following the insufficient balance test, the provided payment link was used. The web-hook successfully received payment confirmation from Paystack, cleared the recorded debt, deducted the toll, and updated the wallet balance.

Visual feedback was provided throughout by the LED array, with colors and blink patterns indicating system status (e.g., idle, processing, success, insufficient funds, queue state).

3. Results and Discussions

This section presents the experimental results from the comprehensive testing and validation of the ATCS prototype. These results are also concurrently discussed in this section of the paper. The findings are derived from real-time transaction logs stored in the Firebase Realtime Database and corroborated by serial monitor outputs and visual LED feedback

3.1. Validation of the Core Transaction Workflow

The purpose of validating the transactional workflow is to enhance transparency and user trust through Proactive Communication. The system’s primary function in processing a toll transaction when a vehicle user has sufficient balance was validated across multiple test runs. As shown in **Table 1**, Vehicle 7a5a3d02, with a measured weight of 2.8 kg, is used to compute a corresponding toll of GH¢1.68 according to Equation (1). The system then queried the Firebase database, confirmed an available balance of GH¢ 8.00, executed the deduction, and updated the balance to GH¢ 6.32 in real-time. A success notification is dispatched via IFTTT, and the transaction is logged in Google Sheets for administrators to gain access to a real-time transaction process. This also enables users to receive immediate emails for transaction success, debt recording, and payment links. This workflow is consistently replicated for other test vehicles (937db7e4, 14973ca3), confirming 100% reliability in the standard operational sequence, where the system accurately computes the transaction for each vehicle at the time of testing. This system, therefore, addresses the limitation in prior work of the inadequate exploitation of real-time communication platforms by implementing a proactive, multi-channel notification strategy using IFTTT. This transparency, evidenced in the consistent logging of all financial field changes as shown in **Table 1** and further explained in Section 3.2, builds user trust and provides authorities with a robust tool for revenue auditing and combating leakage, a critical improvement over opaque, cash-based systems vulnerable to fraud and error.

Table 1. Successful toll transaction record from Firebase Realtime Database.

Date	Time	Vehicle ID	Weight (kg)	Toll (GH¢)	Debt Before	Balance Before	Balance After	Debt After	Notice
03-10-2025	05:18:03	7a5a3d02	2.80	1.68	0.00	8.00	6.32	0.00	Success
03-10-2025	05:18:03	937db7e4	5.40	3.24	0.00	4.50	1.26	0.00	Success
03-10-2025	05:20:03	14973ca3	1.80	1.08	0.00	1.50	0.42	0.00	Success
03-10-2025	05:23:03	7a5a3d02	3.70	2.22	1.00	8.00	4.78	0.00	Success
03-10-2025	05:24:03	937db7e4	4.80	2.88	0.00	5.00	2.12	0.00	Success
03-10-2025	05:25:03	14973ca3	7.70	4.62	5.00	10.00	0.38	0.00	Success
03-10-2025	05:27:03	7a5a3d02	3.40	2.04	0.00	0.00	0.00	2.04	link sent
03-10-2025	05:27:03	937db7e4	1.80	1.08	1.00	1.00	0.00	2.08	link sent
03-10-2025	05:27:03	14973ca3	9.20	5.52	0.00	3.00	0.00	2.52	Success
03-10-2025	05:27:03	937db7e4	10.40	6.24	0.00	8.50	2.36	0.00	Success

3.2. Robust Debt Management and Insufficient Balance Handling

A critical test of the system’s resilience involved scenarios with debt management and insufficient wallet funds. The prototype demonstrated efficient handling of debt and the insufficient account balance of users. For instance, as indicated in **Table 1**, when Vehicle 937db7e3, having a weight of 1.8 kg with the corresponding toll value of GH¢1.08, is presented with a balance of only GH¢1.00, the system prevented the deduction, recorded the full toll amount as a debt, and updated the user’s total debt in Firebase. Concurrently, it triggered a two-stage IFTTT notification, enabling an immediate debt alert followed by a personalized Paystack payment link for the calculated top-up amount.

A study of Vehicle 7a5a3d02 over a period, as shown in **Table 2**, provides compelling evidence of the complete debt management performance lifecycle. The vehicle accumulated a debt of GH¢9.30 across three passages with the respective debts of GH¢5.30, GH¢2.43 and GH¢1.57.

Upon a subsequent top-up of GH¢14.00, the system automatically cleared the entire outstanding debt, deducted the new toll of GH¢2.41, and credited the remaining balance of GH¢2.29 to the user’s wallet. During the next date and time (02-10-2025, 13:29), the toll computed was GH¢1.11, which was deducted from the existing balance of GH¢2.29, leaving a balance of GH¢1.18. For the next passage on 02-10-2025 at 13:32 pm, the toll charged was GH¢1.80. Since a top-up of GH¢5.00 was also made, the system put together the top-up money and the existing remaining balance to get GH¢6.18, from which the current toll of GH¢1.18 was deducted to leave a balance of GH¢4.38. This performance trend of debt management and insufficient balance handling is repeated in the subsequent passages’ dates and times. This process validates the intelligent financial management of the automatic toll collection system. This system therefore has the ability to manage debt and balance insufficiency more effectively compared to FASTag discussed in Section 1.

Table 2. Toll transaction performance log excerpt for Vehicle 7a5a3d02.

Date	Time	Transaction Type	Top Up (GH¢)	Toll (GH¢)	Debt (GH¢)	Balance (GH¢)
01-10-2025	02:35	DEBT	0.00	5.30	5.30	0.00
01-10-2025	15:11	DEBT	0.00	2.43	7.73	0.00
01-10-2025	15:17	DEBT	0.00	1.57	9.30	0.00
02-10-2025	00:06	SUCCESS	14.00	2.41	0.00	2.29
02-10-2025	13:29	SUCCESS	0.00	1.11	0.00	1.18
02-10-2025	13:32	SUCCESS	5.00	1.80	0.00	4.38
02-10-2025	14:19	DEBT	0.00	5.08	0.70	0.00
02-10-2025	18:19	SUCCESS	7.00	3.50	0.00	2.80
02-10-2025	18:26	SUCCESS	0.00	1.22	0.00	1.58
02-10-2025	18:47	DEBT	0.00	4.91	3.33	0.00
02-10-2025	19:11	SUCCESS	8.00	2.01	0.00	2.00

The financial operation of the automatic toll collection system described in this section applies a local financial technology (fintech), which refers to payment platforms, services, and infrastructures that are widely adopted and trusted within a specific national or regional economy. In Ghana, this includes mobile money services such as MTN Mobile Money (MoMo) and AirtelTigo Cash, and local card payment gateways that have become an integral part of daily commercial service, more often than traditional banking or international card networks. Despite the potential of this fintech platform, the existing literature notes

significant underutilization of these locally relevant financial technologies in proposed automated tolling systems [26,27]. These studies often propose generic prepaid models without leveraging the specific, ubiquitous payment channels of the target region. This work directly addresses this gap by deeply integrating the Paystack payment API, a payment gateway that seamlessly supports mobile money, local cards, and bank transfers. The validation of the top-up and automated toll payment and debt clearance cycle shown in **Table 2** and discussed in Section 3.2 proves the novelty of applying this approach. The system does not

merely record debt, but also activates a recovery mechanism by generating a personalized Paystack payment link, thereby enabling real-time settlement via these familiar and widely used payment channels. This design ensures financial accountability while maintaining traffic flow.

3.3. Analysis of Dynamic Weight-Based Equitable Toll Calculation

The transaction data confirms the correct implementation and operation of the dynamic tolling model presented in Equation (1). Charges varied directly in proportion to the measured vehicle weight, ensuring equitable pricing. For example, Vehicle 14973ca3 was charged GH¢1.08 and GH¢5.52 for the respective weights of 1.8 kg and 9.2 kg, as indicated in **Table 1**. Similarly, this direct correlation of

dynamic weight-based toll calculation is observed across all other entries, validating the core principle that toll fees accurately reflect a vehicle’s weight and its potential road infrastructure impact, which is superior to the fixed-fee model. It must be noted that the varying weight, for that matter, the varying toll value is a result of the weight of the vehicle and the weight of the load in it, based on the computation from the mathematical model in Equation (1), at the instance of passing the toll collection point. This demonstrates the fairness of the ATCS because it is based on the amount of weight computed and not the class of the vehicle. This fairness demonstration is also shown in **Figure 5**, which exhibits the expected linear relationship between the weight of the vehicle and the amount of toll charged during the experimental process.

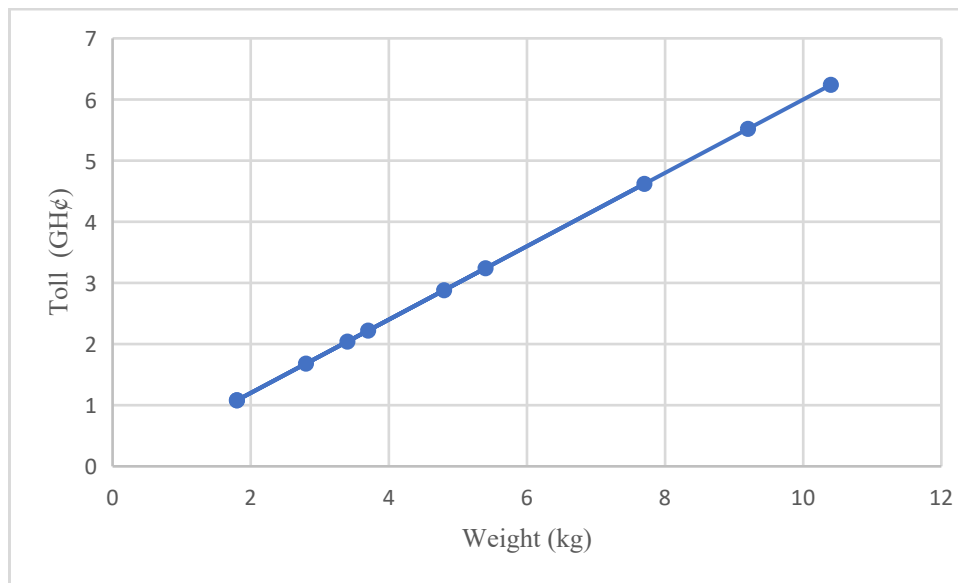


Figure 5. Graph of the weight of a vehicle and its load, and the corresponding toll charged.

The use of the WIM sensor and catering for non-inclusion of the weight of its mounting assembly modeled in Equation (1) demonstrates the system’s ability to enact a proportional charging model where toll fees vary directly with the measured vehicle mass. This validates the implementation of a more equitable toll payment principle, where fees reflect the actual road wear and spatial footprint of a vehicle, a significant improvement over the fixed-fee models reported in literature. This integration provides a scalable technical basis for implementing graduated toll policies that can manage traffic demand and infrastructure maintenance costs more effectively.

3.4. Analysis of Real-Time Vehicle Toll and Financial State Performance

This section presents a case study of the Vehicle tagged 7A5A3D02, utilizing the graphical representation in **Figure 6** to validate the operational and financial logic of the ATCS. The figure visualizes the system’s financial management, tracking the dynamic interplay between debt, balance, and top-up events. For clarity, a 12-h time format is used in **Figure 6** compared to a 24-h time format in **Tables 1** and **2**. A critical period from 2:35 AM to 3:17 PM on October 1st, as detailed in **Table 2** and **Figure 6**,

demonstrates the system’s protocol for handling insufficient funds. During this time, the vehicle’s account lacked the balance to cover the accumulating tolls, and no top-up was initiated. All the same, the system correctly recorded each unpaid toll as an increasing debt, ensuring financial accountability without impeding the vehicle’s passage. This is a novelty introduced into this work, allowing users to use the road and pay later when they top up. However, a limit should be introduced in future work to prevent users from accumulating debt beyond the approved threshold. This scenario was resolved on October 2nd, 2025, at 12:06 AM, when a top-up of GH¢14.00 was deposited. The system automatically executed a comprehensive update of the financial transaction where the entire outstanding debt was cleared, the current toll of GH¢2.41 was deducted, and a remaining balance of GH¢2.29 was left in the account.

The preservation of a positive balance post-transaction is a direct result of the logic embedded in Equation (2), specifically the inclusion of the financial buffer. This buffer is a crucial feature that ensures users retain a residual balance after clearing their debts, proactively preventing immediate recurrence of insufficient funds and promoting a seamless user experience.

The analysis of Vehicle 7A5A3D02 provides evidence of the system’s operational excellence. It successfully validates the integration of the weigh-in-motion sensor for equitable, dynamic tolling and demonstrates intelligent debt management and automated reconciliation. The case study proves that it enables non-stop vehicle motion, ensures transparent financial accountability, and fosters a user-centric experience through design features like the top-up buffer.

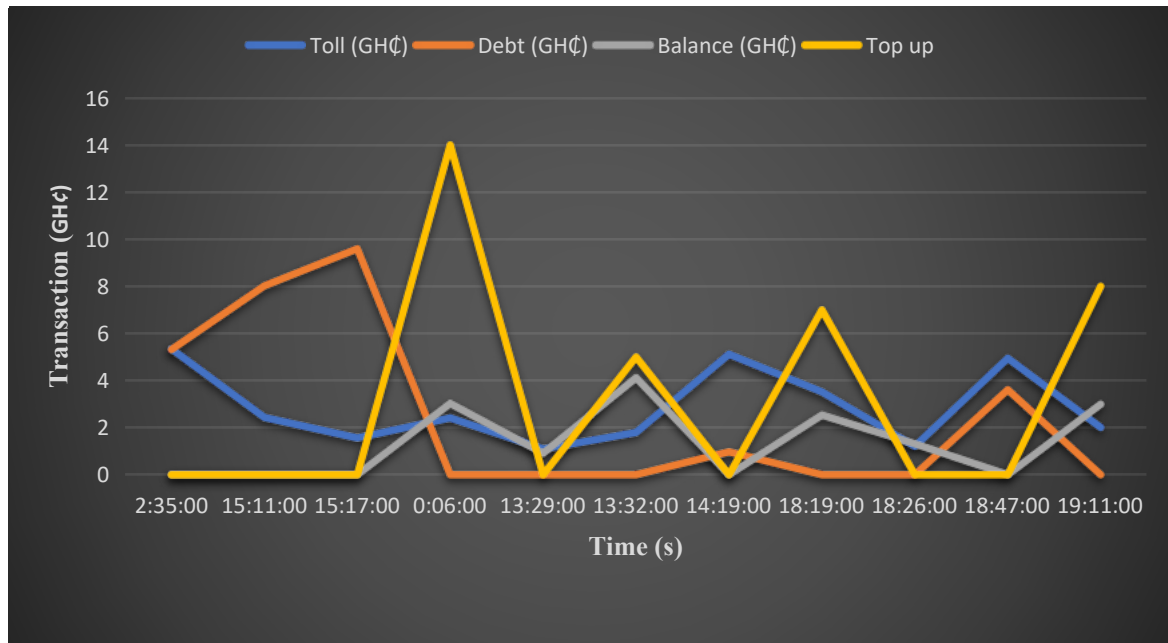


Figure 6. Real-time vehicle toll transaction performance.

3.5. Advancing towards a True Free-Flow Architecture and Pathways to Deployment

Many existing models remain conceptually tied to physical gate mechanisms for the enforcement of toll collection. This project’s operational validation demonstrates a shift towards a true free-flow, gateless paradigm. The system’s logic relies entirely on automated sensor verification, cloud-based financial checks, and post-transaction accountability via debt recording and notifications. The

developed system presents a cohesive, context-aware solution that integrates vehicle identification, equitable dynamic pricing, locally relevant digital payments, and robust financial management into a single, gateless architecture. The results confirm that the proposed system meets its design specifications and offers tangible advancements for improving the existing models. The successful handling of both sufficient and insufficient balance scenarios, as discussed in Sections 3.2, 3.3, and 3.5, without a physical barrier proves the viability of this approach. The multi-tier

LED feedback system further supports this proof, thereby providing the necessary operational confidence for free vehicle movement. This architectural choice is fundamental to achieving the core objective of eliminating congestion at the toll point itself and its associated problems.

The prototype confirms the technical feasibility of the proposed architecture using affordable, off-the-shelf components. However, the discussion must also acknowledge the limitations inherent in a prototype-scale model. The use of a 20 kg load cell and model vehicles, while sufficient for proof of concept, underscores the need for industrial-grade, high-capacity WIM sensors and long-range UHF RFID readers in a full-scale deployment. Furthermore, while the cloud-based architecture (Firebase, Render) offers excellent scalability, a production system would require enhanced cybersecurity measures, including end-to-end encryption and integration with national vehicle registries to prevent tag cloning or fraud. The provision of these enhanced security features is not the goal of this research, but will be considered in the subsequent study.

4. Conclusions

This study successfully designed, constructed, and validated a functional prototype of an ATCS that integrates IoT, RFID, and digital payment technologies into a cohesive solution. The system achieves its core aim of enabling seamless, cashless toll transactions through the synergistic operation of an ESP32 microcontroller, an MFRC522 RFID reader for vehicle identification, and a load cell for WIM measurement. The implementation of a dynamic, weight-based toll algorithm introduces a fair and transparent pricing model that directly addresses the inequity of fixed-rate systems. Testing and validation demonstrated the prototype's robustness, confirming reliable transaction processing, intelligent debt management with automated Paystack top-up links, and automated debt clearance upon payment. By leveraging Firebase for real-time data management and IFTTT for user notifications and logging, the system enhances transparency and accountability. Its gateless, free-flow design offers a practical solution for reducing traffic congestion associated with manual toll plazas. The system also shows how integrating affordable IoT

components with existing digital payment ecosystems can improve traffic efficiency, secure revenue, and support sustainable urban mobility, particularly in developing economies. Overall, the project demonstrates that a fair, efficient, and user-centric tolling system can be achieved through the integration of dynamic vehicle weight sensing, cloud intelligence, local fintech, and proactive communication, providing a scalable model for modernizing toll systems. Future work will focus on deploying industrial-grade hardware, strengthening cybersecurity protocols, and integrating with national vehicle databases to transition this promising prototype into a full-scale implementation.

Author Contributions

Conceptualization, M.K.T. and S.A.B.; methodology, S.A.B. and G.S.; software, S.A.B.; validation, G.S., M.G.O. and Y.O.; formal analysis, M.K.T.; investigation, S.A.B., G.S., M.G.O. and Y.O.; resources, S.A.B., G.S., M.G.O. and Y.O.; data curation, S.A.B.; writing—original draft preparation, S.A.B., G.S. and M.G.O.; writing—review and editing, M.K.T. and P.A.A.; visualization, S.A.B. and P.A.A.; supervision, M.K.T.; project administration, M.K.T. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this work, the authors used DeepSeek to assist in generating c++ script code for the system operation and in checking and correcting grammatical errors. The authors subsequently reviewed and edited the content as necessary and take full responsibility for the final content of the published article.

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