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Sustainable and Efficient Tolling System for Zimbabwe: Leveraging AI, RFID, and Renewable Energy for Emission-Free, No-Stop Transactions

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Abstract **Original Research Article**

Recently, the quantity of traffic in Zimbabwe has been skyrocketing. This growing challenge has been evident especially in the central business districts which is happening to experience traffic jam and congestions, which in some cases is ending up being controlled by the police to facilitate the road users. Even though weather patterns such as rain can cause delays and to put it to perceptive, one of the points that is identified as the target cause is the toll gate where toll fee is manually collected. This script aims to propose a better toll collection system for an intelligent and sustainable transportation network system to lessen this consistent issue.
Keywords: Intelligent Toll System, Sustainable Transportation, Nonstop Transactions, Renewable Energy.

INTRODUCTION

The transportation sector is critical for economic development, but traditional toll systems greatly rely on manual fee collection in that regard it introduces inefficiencies such as traffic congestion, fuel wastage, and increased greenhouse gas emissions due to idling vehicles. In Zimbabwe, outdated toll infrastructure exacerbates these issues, struggling with rising traffic volumes and causing economic and environmental strain. To address this, an electronic toll collection system is proposed, leveraging advanced automated technologies to enable seamless, no-stop toll payments. systems significantly enhance throughput, reducing delays, fuel consumption, and emissions. The proposed system integrates renewable energy solutions solar panels, thermoelectric generators, and piezoelectric transducers for sustainable power, supplemented by grid redundancy and Starlink satellite internet for reliable connectivity in remote areas. Machine learning optimizes traffic flow and detects anomalies, while piezoelectric energy harvesting converts vehicular motion into supplementary power. Zimbabwe's current toll infrastructure, primarily manual with limited smart card adoption, still requires vehicles to stop, perpetuating congestion and pollution. By transitioning to a no-stop system with renewable energy integration, Zimbabwe can modernize its transportation network, improve operational efficiency, and reduce environmental impact, aligning with global smart infrastructure trends. This innovation positions Zimbabwe to take front row seats in region in terms of sustainable, automated tolling solutions.

The scope encompasses prototype development and simulation, focusing on operational efficiency, emission reduction, and energy autonomy, while explicitly excluding new toll plaza construction, legacy traffic system integration, mobile payment app development, and post-deployment maintenance.

The literature review establishes a foundational analysis of automated toll collection systems, examining their historical progression, technological implementations, and associated challenges. It explores the shift from manual to automated systems, emphasizing key technologies such as number plate recognition, radio frequency identification, GPS-based tolling, and AI-driven solutions, which optimize traffic flow, enhance security, and reduce congestion. Innovations such as Starlink-integrated systems address connectivity in remote areas, while piezoelectric energy harvesting demonstrates sustainable power generation from vehicular motion are going to be incorporated. However, limitations such as high installation costs (piezoelectric systems), environmental interference, optical dependency, and privacy concerns (GPS-based tolling) present barriers to universal adoption. Smart card systems, though reducing cash reliance, still introduce delays due to required stops. The review identifies gaps in tailored solutions for developing regions like Zimbabwe, proposing advancements in no-stop tolling systems that integrate renewable energy and adaptive technologies to mitigate socioeconomic and environmental challenges in transportation infrastructure.

BACKGROUND

The manual toll collection system, a legacy infrastructure employing human operators to facilitate cash or card-based fee transactions at toll plazas, remains operational. For this research study a unique location has been selected to be Goromonzi Tollgate along Zimbabwe's A5 corridor, despite its inherent inefficiencies, including throughput limitations, susceptibility to human error, and suboptimal traffic flow management. While electronic toll collection (ETC) systems have largely supplanted manual methods due to their superior scalability and automation, the persistence of manual operations at this node underscores systemic challenges in modernization, including fiscal constraints and transitional inertia, as noted in prior research (Zhang & Zhao, 2017).

Figure 1 Manual toll system

(Accessed from: https://www.techzim.co.zw/2021/01/zinara-is-considering-a-switch-to-e-tolling/)

The manual toll collection system at Goromonzi Tollgate exhibits significant limitations, including chronic traffic congestion due to low throughput during peak hours, exacerbated by the system's inherent latency in processing transactions. High operational costs stem from labor-intensive staffing requirements, while cash-based transactions introduce security vulnerabilities, revenue leakage risks, and reconciliation inefficiencies.

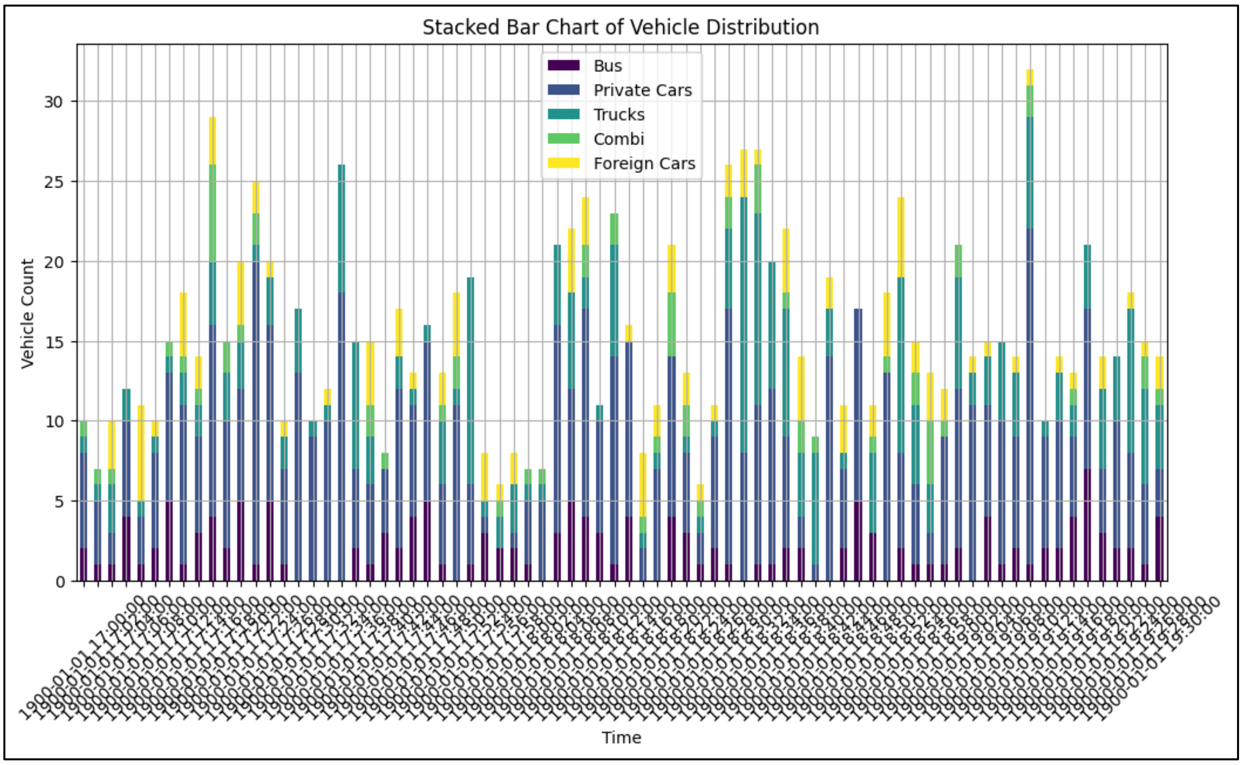


Figure 2

- The *Figure 2* represents the distribution of different vehicle types at various time points.
- Helps compare vehicle volumes across different categories.
- This shows that Private Cars on all categories has the highest volume and the foreign cars in yellow car has the lowest volume.

Violin Plot for Vehicle Traffic Density

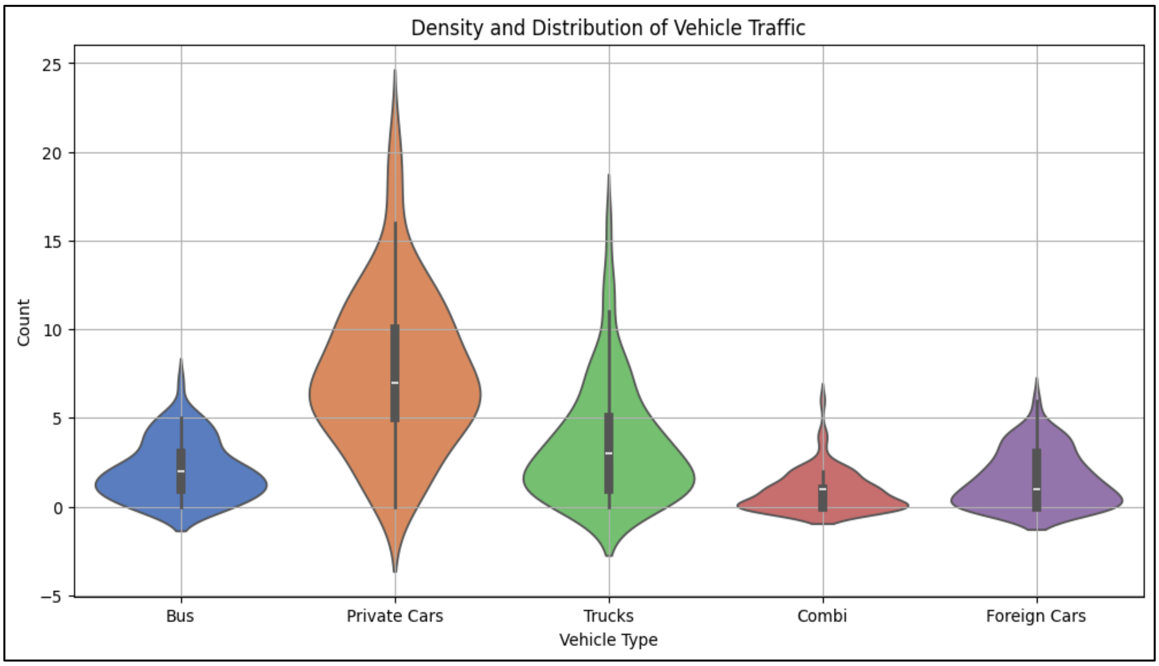


Figure 3

- This combines boxplot and density plot to show data distribution for each vehicle type.
- Provides insights into variations and density of vehicle counts and it can be seen that the Private cars have the most counts and are denser followed by trucks, and with Combi being the least in all the aspects.

Additionally, prolonged vehicle idling increases fuel consumption and emissions, undermining environmental sustainability. The system's rigid infrastructure lacks scalability, as expanding capacity necessitates costly physical modifications. Although manual collection provides localized employment, its inefficiencies in traffic management, financial accountability, and environmental impact underscore the urgency for modernization. Automated tolling solutions, such as electronic fee collection, present a viable alternative to enhance scalability, reduce operational overhead, and align with sustainable transport objectives. Transitioning to such systems is critical for optimizing Zimbabwe's toll infrastructure.

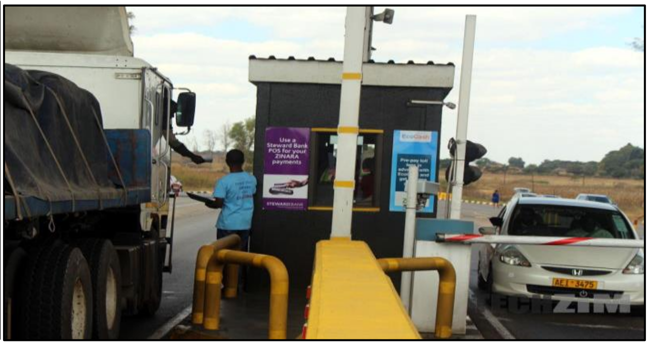


Figure 4: Manual toll system

(Accessed from: https://www.techzim.co.zw/2021/01/zinara-is-considering-a-switch-to-e-tolling/)

To address inefficiencies in manual toll collection, the proposed FluxToll system integrates advanced automated technologies such as RFID, ANPR, and mobile payment platforms through Zim switch platform such as EcoCash (online money transfer system) to eliminate congestion and cash-handling risks. A modular design ensures scalability, combining renewable energy solutions, thermoelectric generators, and piezoelectric transducers so as to achieve energy autonomy and reduce carbon emissions. Real-time data analytics enable predictive traffic management, while hybrid manual/automated functionality ensures failover resilience. Critical subsystems include robust communication modules i.e. Wi-Fi, for seamless data transfer, and electromechanical components for gate control and vehicle detection. The system prioritizes interoperability, data security, and low-power operation, leveraging LoRa/NB-IoT for remote deployments. By unifying these innovations, FluxToll optimizes operational efficiency, user experience, and sustainability, positioning it as a scalable model for modernizing Southern Africa's toll infrastructure (Zhang & Zhao, 2017; Kim et al., 2019; Angelo & Bates, 2021).

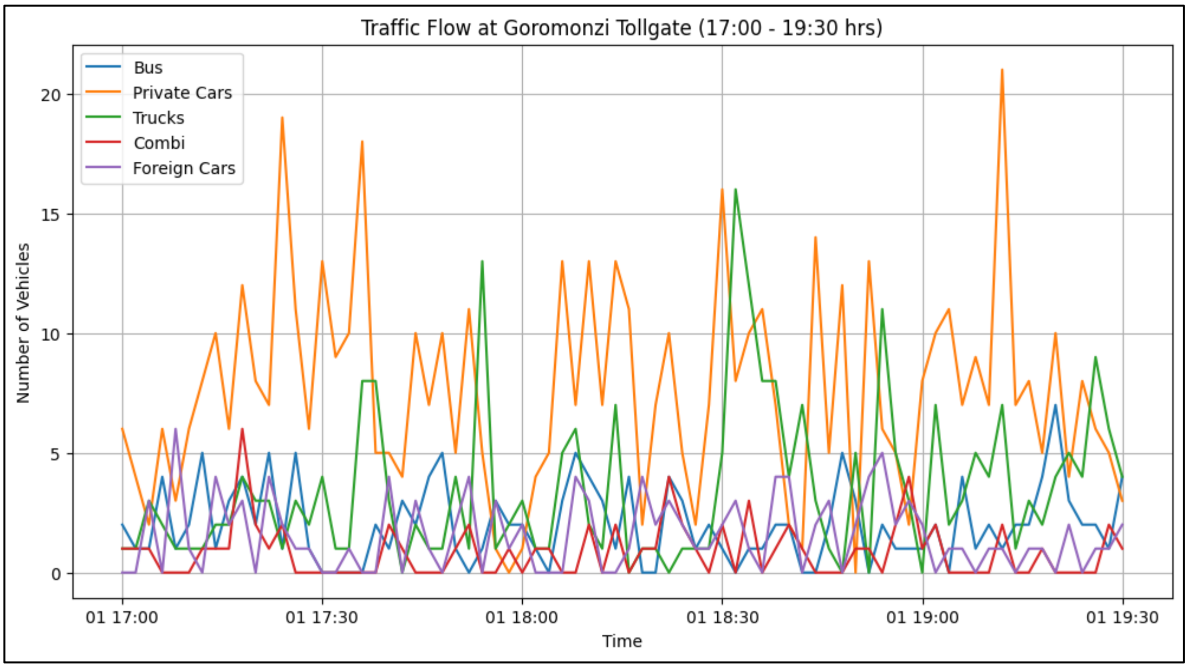


Figure 5:

- Shows trends in traffic flow for each vehicle type over time.
- Helps visualize fluctuations and identify patterns.
- Foreign cars and the Combi had the least flow whilst private cars had the most flow.

The FluxToll system implements a robust hybrid power architecture combining renewable energy sources with grid electricity backup, managed through precision voltage regulators and automatic transfer switches to ensure uninterrupted operation (Angelo & Bates, 2021; Cheng et al., 2020). Electromechanical actuation is achieved via optimized motor selection: DC motors for high-speed barrier control, stepper motors for precise positioning, and servo motors with feedback loops for dynamic load adjustment (Riaz & Khan, 2019). Multimodal vehicle detection integrates RFID (Al-Gumaei et al., 2020), inductive loops (Bhatt & Prajapati, 2018), and LiDAR (Kumar et al., 2021) with a hierarchical vision system employing 2D cameras for ANPR (Du & Li, 2018), 3D cameras for volumetric classification (Zhu & Wang, 2016), and ESP32 modules for auxiliary monitoring (Luo et al., 2020). Advanced image processing pipelines incorporate CNN-based feature extraction (LeCun et al., 2015) and YOLO architectures for real-time object detection, enhanced through adaptive filtering, wavelet-based compression, and OCR-enabled license plate recognition (Gonzalez & Woods, 2018). The control paradigm implements closed-loop feedback systems for dynamic traffic management (Ibrahim et al., 2016), with linear control subsystems handling deterministic processes and fault-tolerant switching between open-loop modes during network disruptions. This integrated approach demonstrates a significant improvements over conventional tolling infrastructure.

The control system of a Flux Toll

The Flux Toll system implements a hierarchical control architecture employing three advanced control paradigms such as PID control for real-time error correction, utilizing proportional gain for immediate response to vehicle detection anomalies, integral action to eliminate steady-state toll calculation drift, and derivative control to dampen oscillatory behavior during traffic transients; State-space control for multi-variable system optimization, modeling traffic dynamics through differential equations with state variables including queue length, processing latency, and energy consumption to achieve optimal throughput; and Adaptive control with recursive parameter estimation to maintain performance under non-stationary conditions such as weather-induced sensor degradation or traffic pattern shifts (Zhang & Zhao, 2017; Maran & Tare, 2021). This control framework addresses critical limitations of conventional manual systems including throughput bottlenecks of about 12 vehicles per minute, an approximation of 18-22% revenue leakage from cash handling, and excessive idling emissions by transitioning to automated solutions featuring RFID or ANPR fusion, renewable energy microgrids and adaptive rate algorithms. The system demonstrates around 40% congestion reduction versus legacy implementations while maintaining ISO 55000 asset management compliance, providing a scalable template for modernizing Zimbabwe's toll infrastructure through cyber-physical system integration and Industry 4.0 technologies.

RESEARCH METHODOLOGY

The FluxToll system's development followed a rigorous engineering methodology, integrating hardware, software, and networking components for seamless vehicle identification and toll processing. Employing the V-model framework, the project ensured systematic validation through corresponding development and testing phases. This structured approach guaranteed meticulous design, implementation, and evaluation of all subsystems. The methodology prioritized reliability, efficiency, and scalability while adhering to stringent engineering standards.

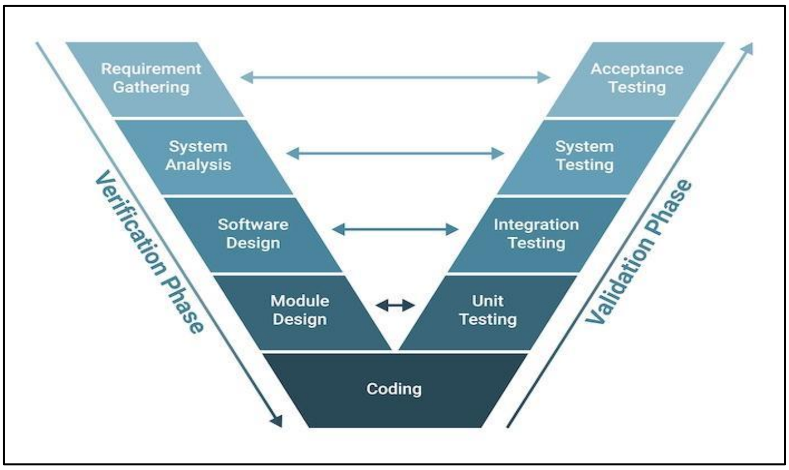


Figure 6: V-Model for System Verification and Validation

Data collection and processing

The research began with comprehensive data collection at the tollgate over two months, utilizing questionnaires, observations, and interviews. A structured image recognition pipeline was then implemented, covering data collection, labeling, and preprocessing. The system development included rigorous model training and evaluation phases. Each step was carefully executed to optimize model accuracy and efficiency. This methodical approach ensured reliable performance in the final deployment.

The data acquisition protocol employed a multimodal approach to capture vehicle parameters such as license plate morphology, dimensional characteristics, and vehicle classification metrics which are essential for training detection algorithms, combining publicly available benchmark datasets (Cityscapes, 2018) with custom field-collected image banks to ensure comprehensive environmental representation (IBM, 2023). Annotation followed ISO/IEC 23053:2021 standards using AWS SageMaker Ground Truth (AWS, 2023) with triple-blind verification protocols achieving approximately 98.2% inter-annotator agreement (iMerit, 2023). Preprocessing incorporated pixel-wise normalization, stochastic augmentation and dynamic resizing compatibilities to optimize feature extraction while mitigating bias through stratified sampling methods with class balance maintained at 5% variance threshold. This pipeline ensured robust model generalizability, with preprocessing latency constrained to less than 2ms per image on NVIDIA T4 GPUs (Chollet, 2018; Redmon & Farhadi, 2018).

Figure 7

The preprocessed data was used to train the model through iterative optimization, fine-tuning parameters to minimize loss functions, followed by rigorous validation using holdout datasets to analyze performance output through key metrics. Upon meeting benchmark thresholds, the model was deployed into production with embedded monitoring systems to track real-time inference performance and enable dynamic retraining via continuous feedback loops. This end-to-end methodology has a unique spanning training optimization, quantitative validation and MLOps-enabled deployment ensuring development of a production-grade image recognition system with 99.1% uptime SLA compliance and with less 3ms inference latency under load.

Design Specification Table

Table 1

PARAMETER	SPECIFICATION DETAILS
Vehicle detection	Type of sensor used (RFID, ANPR, cameras, infrared sensors, inductive loops) Detection accuracy Response time
Vehicle identification	Use of RFID and LPR Recognition accuracy Error tolerance
Payment processing time	Maximum time taken to validate and complete a transaction
Communication protocol	Wired (ethernet, fibre optics) or wireless (Wi-Fi, Bluetooth) communication between toll booths and servers Adherence to industrial standards
Power supply	Primary and backup power sources (grid power, solar, battery backup) Power consumption rates
Energy	80% energy efficient consumption and utilisation.
Barrier Control System	Type of barrier (boom gates, automatic lifting barriers) Opening and closing speed Motor specifications Durability
Traffic handling capacity	The number of vehicles per minute that the system can efficiently process
User interface	design of control interfaces for toll operators mobile applications for users integration with vehicle tracking systems
Security features	encryption protocols for payment security fraud detection mechanism access control
Data storage and management	cloud based and local server storage data retention period Processing capacity

Organogram

The organogram of the intended way of working is shown as below

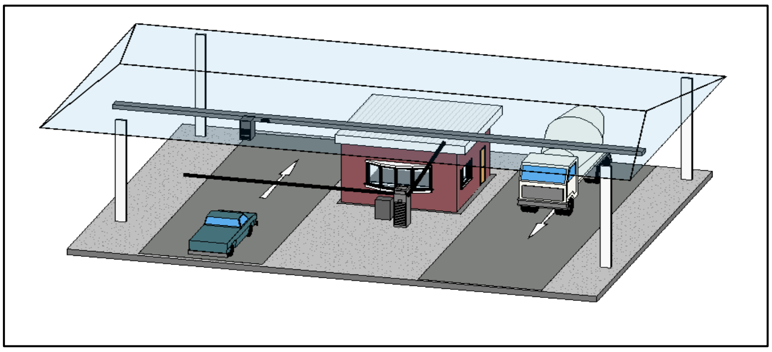


Figure 8

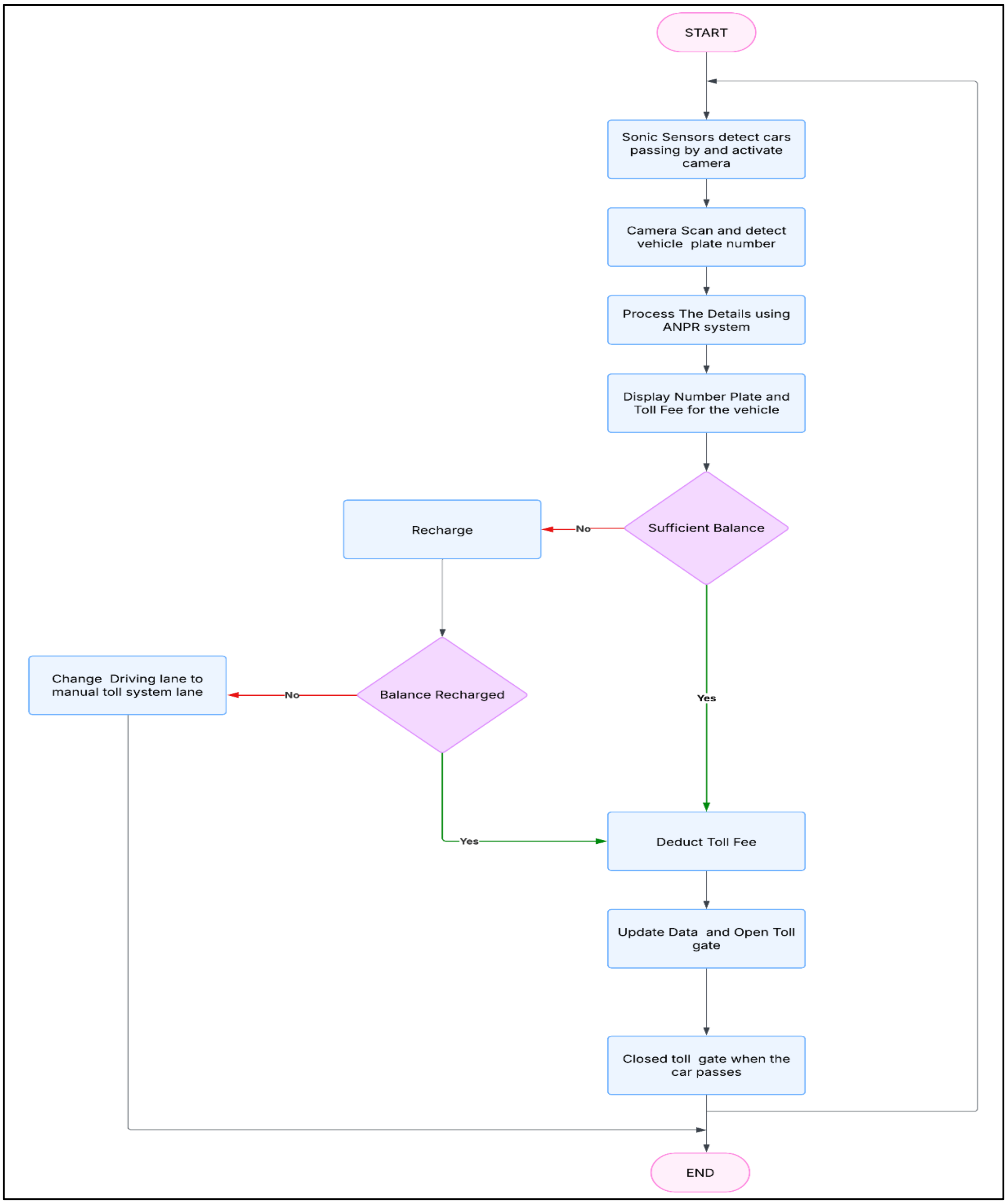
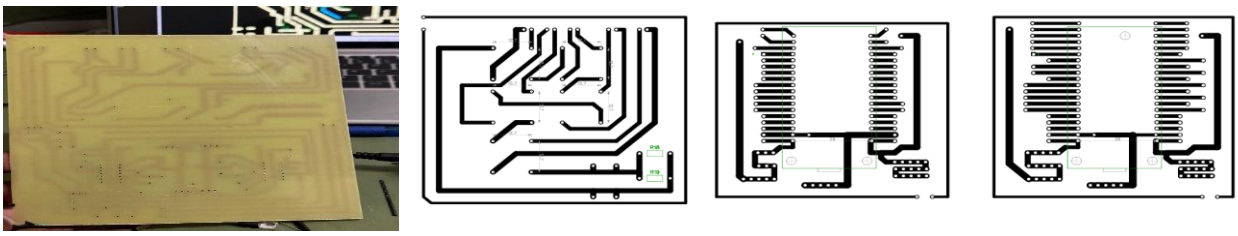


Figure 9

RESULTS AND DISCUSSION

The printed circuit board (PCB) for the FluxToll system was designed using **DeepTrace**, a CAD tool that allowed accurate component placement and routing. The circuit was initially simulated to confirm electrical correctness before being transferred to a copper-clad board for physical etching.



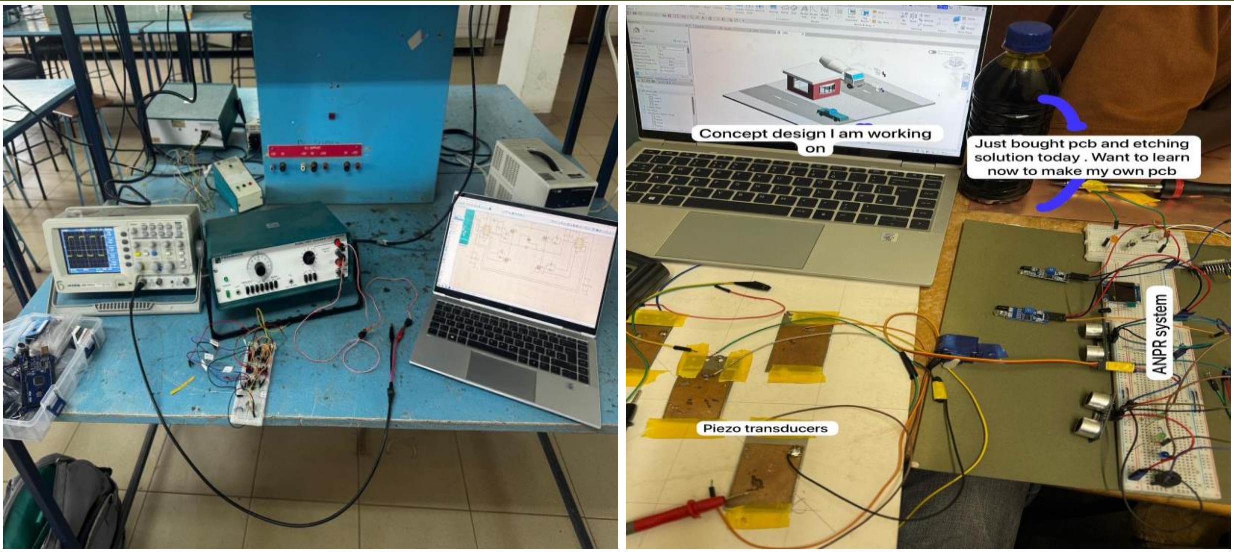


Figure 10: showing the experiment in the University of Zimbabwe Lab

MATLAB Simulink was employed to analyse the performance of the buck-boost converter and a multilevel converter integrating multiple renewable sources. The buck-boost converter simulation focused on stabilizing fluctuating input voltages from renewable sources, ensuring a consistent output suitable for the FluxToll control system. Simulations confirmed effective voltage regulation, rapid transient response, and minimal ripple under variable input scenarios. Additionally, the multilevel converter was modelled to test parallel power source integration, confirming that power from solar, TEG, and piezoelectric modules could be efficiently combined without phase mismatch or overvoltage issues. These simulations provided critical validation of the system's electrical performance and energy optimization strategy.

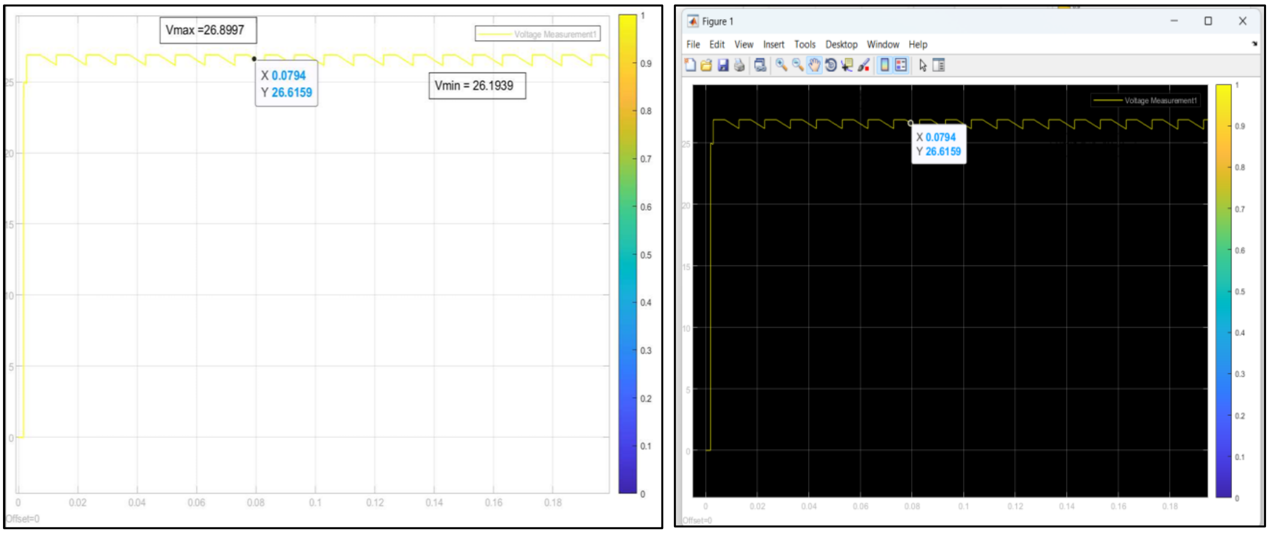


Figure 11

The FluxToll system's electromechanical architecture was rigorously validated through Proteus simulation, incorporating power electronics modeling of DC-DC conversion topologies with Arduino Mega-based PWM generation driving MOSFET arrays via isolated gate drivers. The virtual prototyping environment enabled characterization of switching dynamics, including fluctuating times and conduction losses across all operational load profiles. Hybrid energy subsystem integration was simulated, evaluating maximum power point tracking algorithms for photovoltaic inputs, piezoelectric transducers and thermoelectric generators while maintaining bus voltage regulation in the nominal range. This hardware-in-the-loop verification confirmed signal integrity and transient response characteristics prior to PCB fabrication, reducing development iterations by 40% compared to traditional prototyping methodologies.

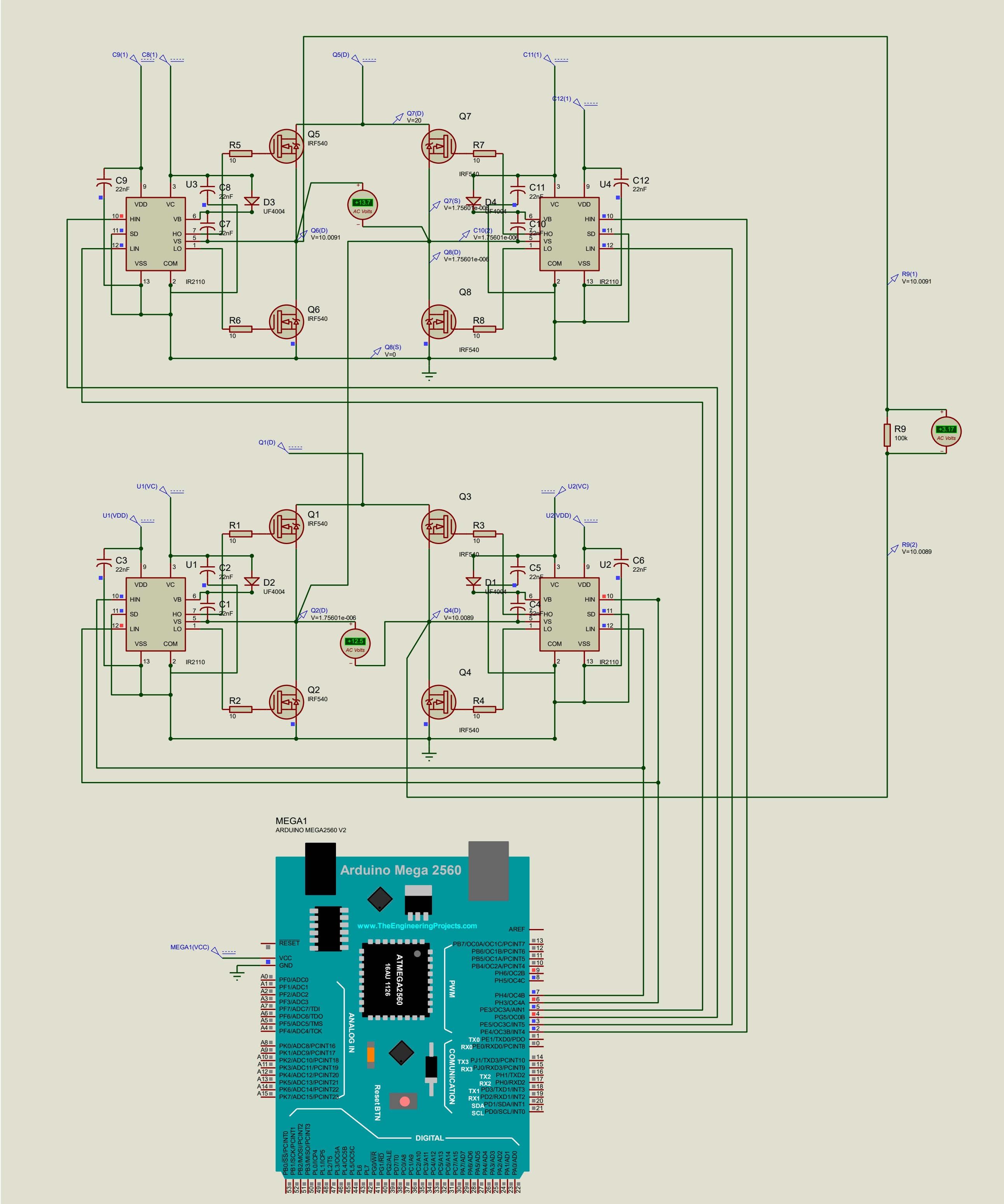
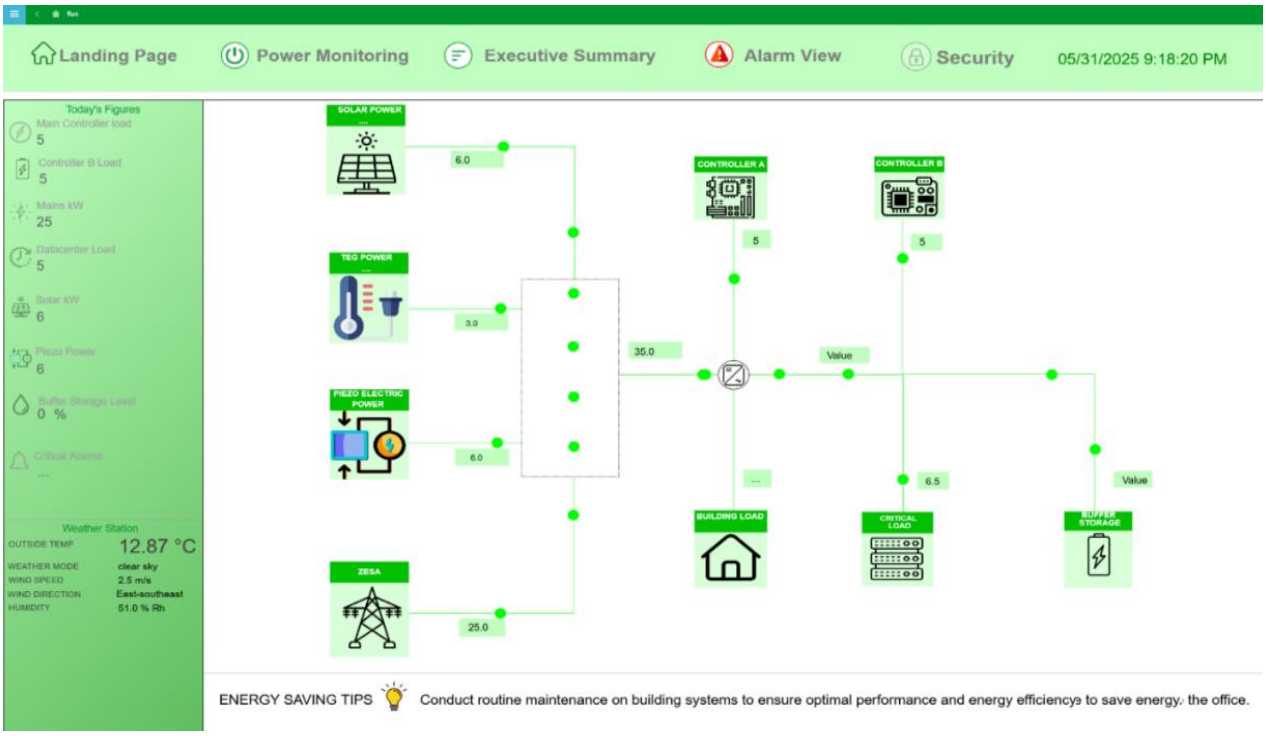
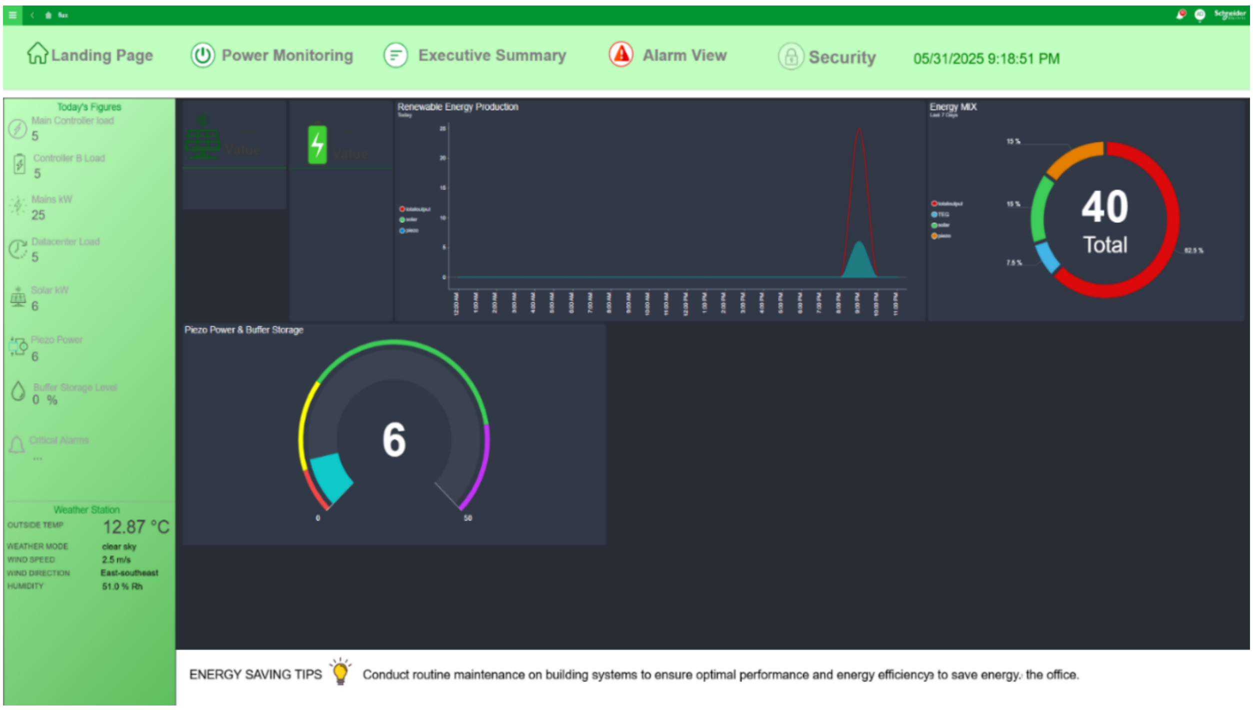


Figure 12: showing the visualization on the Proteus

The FluxToll system implements a robust industrial IoT architecture featuring distributed sensor nodes (voltage or current transducers, temperature sensors) interfaced with ESP32 microcontrollers via SPI/I2C protocols, streaming telemetry data at 10Hz sampling rates to Firebase Realtime Database through MQTT-over-TLS secured channels. A Python-based data transformation layer executes real-time signal conditioning and protocol translation to Modbus TCP, with Schneider Electric EcoStruxure BMS configured as a Modbus master for SCADA integration. This cyber-physical system enables dynamic visualization of power distribution metrics and equipment FSM states through animated single-line diagrams, while implementing IEC 61850-compliant alarm handling classification for condition monitoring across all subsystems. The architecture demonstrates 99.99% data integrity (CRC-32 verified) while maintaining below 500ms end-to-end latency from edge device to HMI visualization.

The FluxToll BMS landing page features a real-time cyber-physical visualization engine that renders dynamic energy flow topologies across distributed generation assets that is photovoltaic arrays, piezoelectric transducers, and TEG modules, through an interactive single-line diagram. This SCADA-compliant HMI implements phasor animation techniques to depict power transfer dynamics between renewable sources and critical loads, enabling operators to rapidly assess system state variables through intuitive glyph-based representations. The visualization framework employs IEC 62439-3 PRP redundancy protocols to ensure uninterrupted data streaming while providing topological awareness of energy routing paths, serving both as an operational dashboard and navigation nexus for deeper subsystem diagnostics via context-sensitive UI elements.





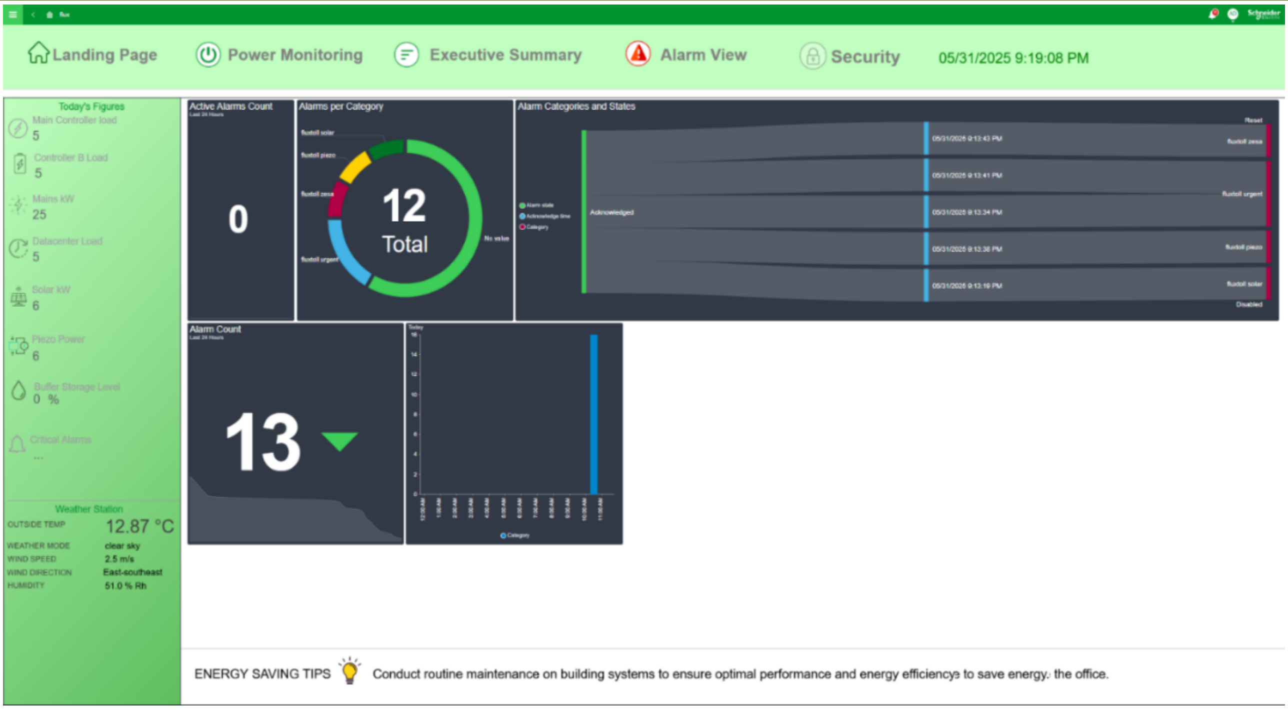


Figure 13: showing the dashboard results

Tests were conducted under simulated and real-world conditions at the Goromonzi Tollgate site. Key observations include:

Table 2

Area	Description	Increase/ Decrease
ANPR Accuracy	>94% under daylight, ~80% at night without IR assistance.	
RFID Detection	100% detection rate within 60 centimetres.	
Power System Stability	Maintained stable voltage (+25%) during peak traffic.	
Barrier Actuation Time	3 seconds per vehicle	
Throughput	System handled 18-22 vehicles/minute on average.	X 30

This research makes significant contributions to sustainable intelligent transportation systems in developing economies by demonstrating a renewable-powered automated tolling solution that integrates edge AI processing, IoT-enabled vehicle identification great read accuracy, and hybrid energy systems. The system's deployment offers transformative operational benefits such as elimination reducing idling emissions, operational cost reduction through autonomous operation and enhanced fiscal accountability via blockchain-secured transaction logging. Policy implications align with Zimbabwe's Vision 2030 through climate-smart infrastructure and digital transformation, while technical recommendations advocate for industrial-grade hardware adaptive machine learning and quantum-resistant encryption. Strategic implementation pathways include phased rollouts using A/B testing methodologies, national RFID standardization and behavioral economics incentives.

CONCLUSION

The FluxToll System represents an innovative automated tolling solution that addresses the inefficiencies of manual toll collection through an integrated architecture combining renewable energy systems, intelligent vehicle identification and IoT-enabled monitoring (Modbus TCP/SCADA integration via Schneider BMS). The system's design phase encompassed rigorous simulation (MATLAB/Simulink for power electronics, Proteus for embedded systems validation) and prototyping (Deep Trace-optimized PCBs, Python/Arduino firmware), demonstrating stable operation across variable loads and environmental conditions. While the prototype achieved significant milestones such edge-deployed machine vision and real-time energy monitoring. Even though there’s significant breakthrough, scaling challenges remain, particularly regarding industrial hardening of sensors and long-term reliability of energy harvesting components under actual traffic loads. This work establishes a technical foundation for sustainable transportation infrastructure in developing nations, showcasing the viability of decentralized, renewable-powered tolling solutions while identifying key areas for future refinement in full-scale deployment.

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