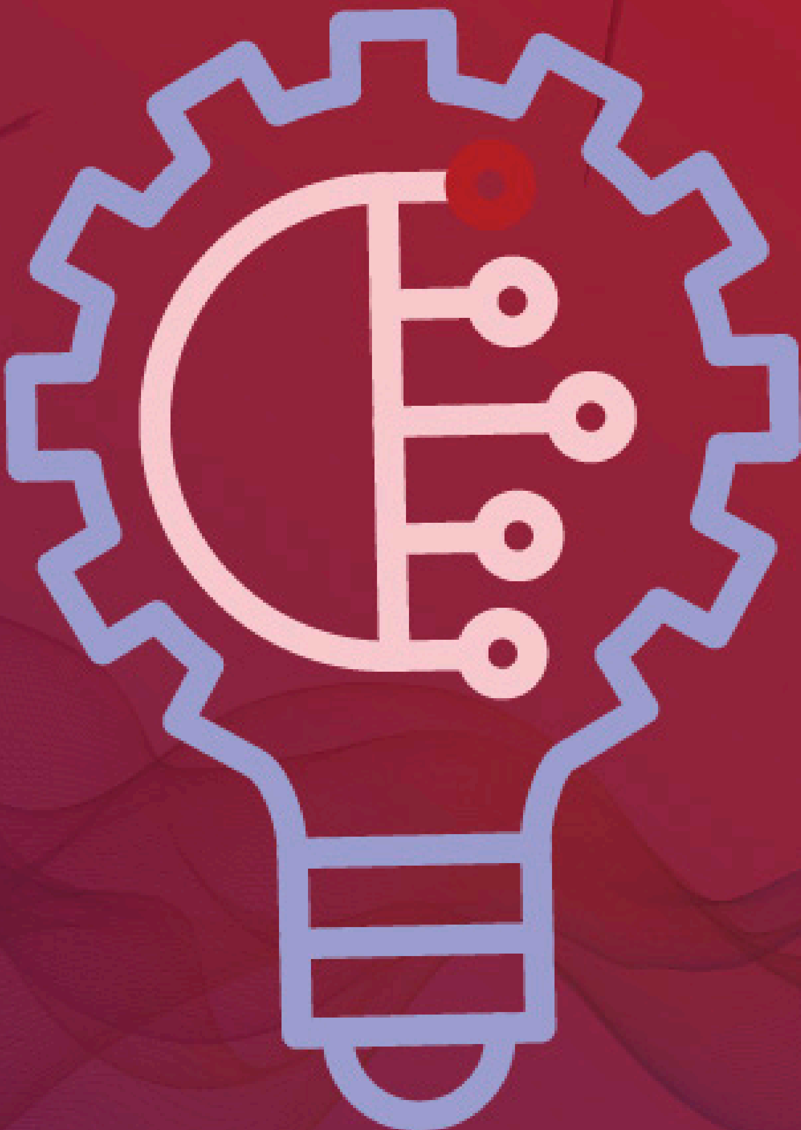
AMERICAN JOURNAL OF
ICT AND INNOVATION (AJICTI)

VOLUME 1 ISSUE 1 (2026)



PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of ICT and Innovation (AJICTI)

Volume 1 Issue 1, Year 2026
https://journals.e-palli.com/home/index.php/ajicti

Design and Development of an AI-Driven Carbon Footprint Calculator for The Transport Sector in Zambia

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Article Information

Received: November 01, 2025

Accepted: January 14, 2026

Published: September 09, 2026

Keywords

AI-Driven Carbon Footprint Calculator,Behavioral Change, Carbon Emissions, Emission Reduction, Environmental Management Transport Sector, Fuel Efficiency, Multilingual Interface, Sustainable Transport, Zambia

ABSTRACT

Zambia's transport sector contributes significantly to greenhouse gas emissions, largely due to its reliance on fossil fuel-powered vehicles, inefficient transit systems, and underdeveloped public transportation infrastructure. This project presents the design and development of an AI-driven carbon footprint calculator tailored to Zambia's transportation context. The tool is intended to provide policymakers, transport operators, and the general public with actionable insights by leveraging machine learning to analyze emissions data. The system integrates data on fuel consumption, vehicle classifications, traffic flow patterns, and environmental variables to build predictive models. Algorithms such as random forest regression will be applied to estimate transport-related emissions and generate scenario-based projections, such as the effects of adopting electric vehicles or improving traffic efficiency. Results will be delivered through an interactive, web-based dashboard to promote public awareness and support sustainable decision-making. The tool will undergo rigorous testing using data from both urban and rural environments to ensure contextual relevance and accuracy. Anticipated outcomes include detailed emission profiles, increased public engagement, and support for evidence-based policy interventions, including fuel efficiency strategies and low-carbon transport planning. The project also addresses common limitations, such as data scarcity and inconsistent digital infrastructure, by incorporating offline functionality to enhance accessibility and usability.

INTRODUCTION

Climate change stands as one of the greatest environmental challenges of the modern era, with far-reaching effects on natural systems, human health, and global economies. Among the major contributors to greenhouse gas (GHG) emissions, the transport sector remains a key source, producing nearly one-quarter of the world's fuel-related carbon dioxide emissions (IPCC, 2022). Road transport is the dominant component of this sector, especially in developing regions where rapid urban growth, rising populations, and expanding economic activity have led to increased vehicle use (IEA, 2023). In Sub-Saharan Africa, factors such as aging vehicle fleets, low fuel standards, and inadequate transport infrastructure further intensify emission levels, highlighting the urgent need for localized solutions. Zambia, a landlocked nation in Southern Africa, depends heavily on its road network, which handles more than 90% of both passenger and freight transport (RTSA, 2021; ERB, 2021). The majority of vehicles in operation are imported second-hand units, typically older than twelve years. Combined with deteriorating road conditions and inconsistent fuel quality, this has resulted in inefficient fuel consumption and elevated carbon emissions. Although there is growing awareness of the need to track and manage transport emissions, Zambia still lacks an accessible AI-based tool that offers users meaningful, data-driven strategies to reduce their carbon footprint. Most existing international carbon calculators are designed for developed regions, relying on up-to-date fleets, precise user data, and high English proficiency factors that limit their effectiveness in Zambia. This research focuses on developing an AI-powered carbon footprint calculator customized for Zambia's road transport sector. Unlike conventional calculators, the system does not estimate missing information; rather, it delivers real-time recommendations to help users make informed choices that lower emissions. The tool integrates both backend and frontend components developed in Python, features a multilingual interface (English, Bemba, and Nyanja), and displays results through an interactive dashboard linked to a secure database. In addition, users can export their data in CSV format for personal analysis and long-term tracking. (SQLAlchemy, 2020).

Problem Statement

Climate change is an increasingly pressing global issue, driven primarily by anthropogenic greenhouse gas (GHG) emissions. Among the various sectors contributing to these emissions, transport remains one of the most significant, accounting for nearly 24% of global energy-related CO_2 emissions (IEA, 2023). Road transport alone represents approximately 74% of total transport emissions, with aviation, shipping, and rail contributing the remainder (IPCC, 2022). Rapid urbanization, economic development, population growth, and increasing motorization have all contributed

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to rising transport emissions worldwide, posing serious environmental and public health challenges (World Bank, 2022). In Africa, and specifically Zambia, the transport sector is almost entirely road-based, with passenger vehicles, minibuses, buses, and freight trucks forming the backbone of the national mobility system (RTSA, 2021). Vehicle fleets are dominated by second-hand imports, often exceeding ten years of age, which lack modern emission control technologies. The combination of aging vehicles, poor maintenance practices, low-quality fuel, and inadequate road infrastructure results in inefficient fuel consumption and elevated emissions (AfDB, 2021; ERB, 2021). Fuel adulteration and regional variability in petrol and diesel quality further exacerbate the problem, making accurate emission estimation highly challenging (UNEP, 2020). The accurate measurement of carbon emissions is central to national climate strategies, sustainable transport planning, and international reporting obligations such as Zambia's Nationally Determined Contribution (NDC) under the Paris Agreement (Government of Zambia, 2021). Carbon footprint calculators, which convert activity data such as fuel consumption, vehicle type, and trip frequency into CO_2-equivalent emissions using emission factors, have proven valuable tools globally (Wiedmann & Minx, 2008; DEFRA, 2022). However, most existing calculators are designed for contexts with complete datasets, standardized vehicle fleets, and high literacy levels, which limits their applicability in Zambia. Furthermore, Zambia's linguistic diversity poses additional challenges. While English is the official language, Bemba and Nyanja are widely spoken in both urban and rural communities. Many transport operators, particularly in the informal sector, have limited proficiency in English, reducing their ability to engage with English-only digital tools (UNESCO, 2020). This linguistic gap often results in inaccurate data entry, reduced adoption of digital solutions, and exclusion from climate awareness initiatives. Given these factors, there is a clear need for a localized, AI-driven, and multilingual carbon footprint calculator tailored to Zambia's transport sector. By integrating local emission factors, vehicle characteristics, operational behavior, and multilingual interfaces, such a tool can empower users with accurate information about their emissions and provide actionable recommendations to reduce their carbon footprint (Zhang *et al.*, 2021; Xu *et al.*, 2020) . Artificial intelligence offers significant potential in this context, enabling the provision of context-specific guidance, even where users have incomplete knowledge of fuel consumption or emission mitigation strategies. (Gupta *et al.*, 2021)

Aim of the Study

The aim of this study is to design and develop an AI-driven carbon footprint calculator tailored to Zambia's road transport sector, providing users with accurate emission estimates, practical recommendations.

Main Objectives

To develop an AI-driven carbon footprint calculator for Zambia's road transport sector that generates accurate emission estimates and provides real-time, actionable tips to users.

Specific Objectives

- To implement a web based python calculator with an interactive, real-time emission feedback dashboard.
- Develop an AI module that generates real-time, context-specific emission reduction tips based on user inputs.
- Validate calculator outputs against local emission factors, fuel consumption statistics, and stakeholder feedback to ensure usability and reliability.

Research Questions

- How can an AI-driven carbon footprint calculator interface enhance usability and data accuracy for Zambia's road transport sector?
- How effectively can AI generate real-time, actionable tips to guide emission reduction?
- How do calculator outputs compare with national fuel statistics and local emission factors?

Structure of the Journal

This journal is organized into five chapters: Introduction (Chapter 1), Literature Review (Chapter 2), Methodology (Chapter 3), Results and Analysis (Chapter 4), and Conclusions and Future Work (Chapter 5).

LITERATURE REVIEW

The transport sector is a major contributor to global greenhouse gas (GHG) emissions, with road transport dominating due to rapid urbanization, increased vehicle ownership, and economic growth (IEA, 2023; IPCC, 2022). Accurate measurement and mitigation of these emissions are essential for effective environmental planning. This review examines global and regional transport emission trends, carbon footprint calculation methods, the role of artificial intelligence (AI) in emissions management, multilingual digital tools, and gaps relevant to Zambia.

Global and African Transport Emissions

Globally, transport accounts for roughly 24% of total energy-related CO_2 emissions, with road transport responsible for 74% (IEA, 2023). Emission intensity depends on vehicle age, fuel type, driving behavior, infrastructure quality, and trip patterns (ERB, 2021; UNEP, 2020). Older vehicles, urban congestion, and poor fuel quality amplify emissions, particularly in developing countries (Zhang *et al.*, 2021; Pandey, 2010). In Africa, road transport dominates passenger and freight movement, often relying on aging fleets and informal systems. Fuel quality inconsistency, irregular maintenance, and limited data availability hinder accurate carbon accounting (AfDB, 2021; CSO, 2020; UNEP, 2020). Zambia's transport sector reflects these challenges, with over 90% of movement via road, predominance of second-hand vehicles, and unreliable operational data (RTSA, 2021; ERB, 2021).

Carbon Footprint Calculation

Carbon footprints quantify GHG emissions in CO_2-equivalents

$$(CO_2\text{-e}) = \text{Activity Data} \times \text{Emission Factor}$$

Activity data may include fuel consumption or vehicle type, while emission factors estimate emissions per unit activity (IPCC, 2006; DEFRA, 2022). Existing calculators assume accurate inputs and modern fleets, which are often invalid in Zambia due to data gaps, older vehicles, inconsistent fuel quality, and limited English proficiency among users.

AI Applications in Emission Management

AI and machine learning enhance emission estimation, especially where data are incomplete. Applications include predicting fuel consumption, recommending fuel-efficient driving, route optimization, and maintenance scheduling (Zhang *et al.*, 2021; Xu *et al.*, 2020). Unlike predictive-only models, AI in this study targets context-specific, behavioral guidance, making tools actionable even for users with limited knowledge.

Related Work

Several carbon calculators offer valuable insights

EcoPassenger (Europe) : Estimates emissions per passenger-kilometer for modern fleets; lacks AI guidance and multilingual support (Pandey, 2010).

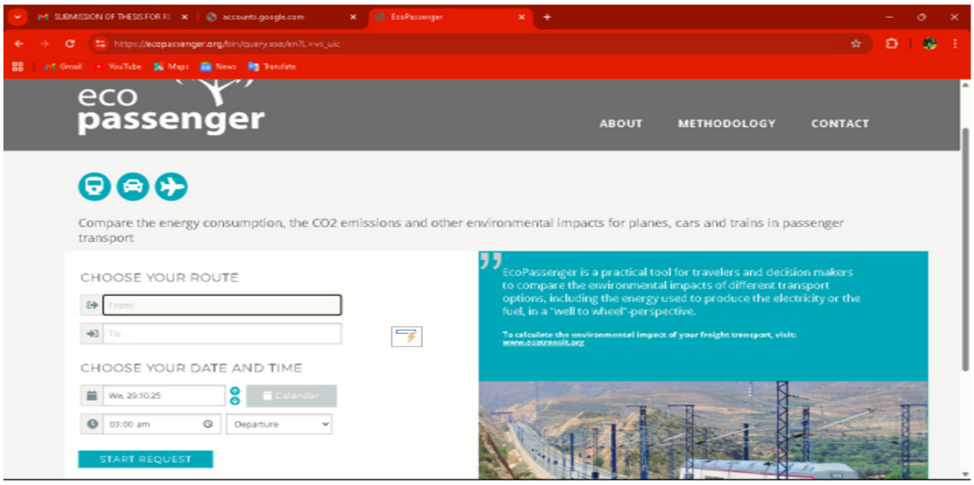

Figure 1: Eco passenger

CarbonTrac.AI (Africa): Targets corporate emissions; limited individual-level guidance and no local language support (CarbonTrac, 2023).

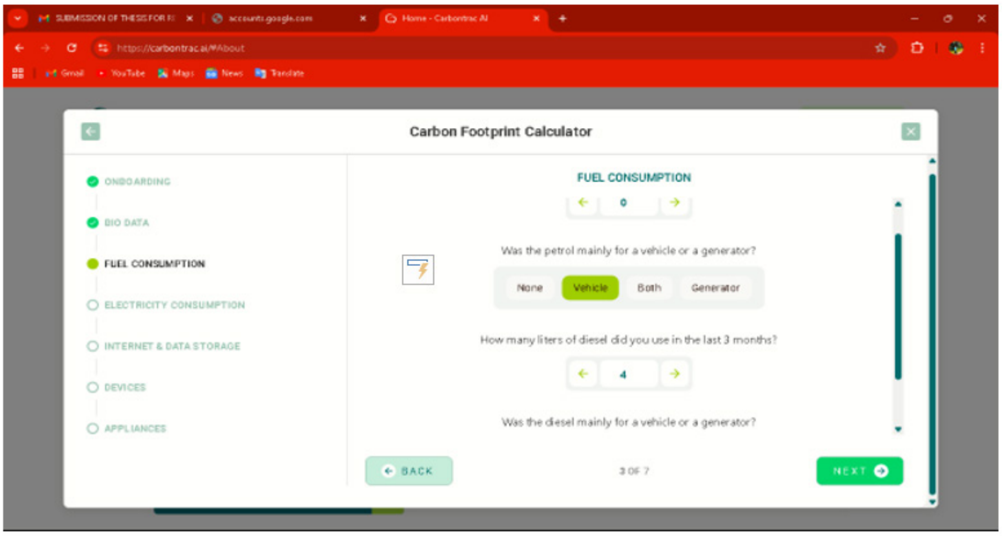

Figure 2: Carbon track AI

MyCarbon (Global): Mobile app with GPS tracking and offsets; requires advanced sensors and connectivity (MyCarbon, 2023).

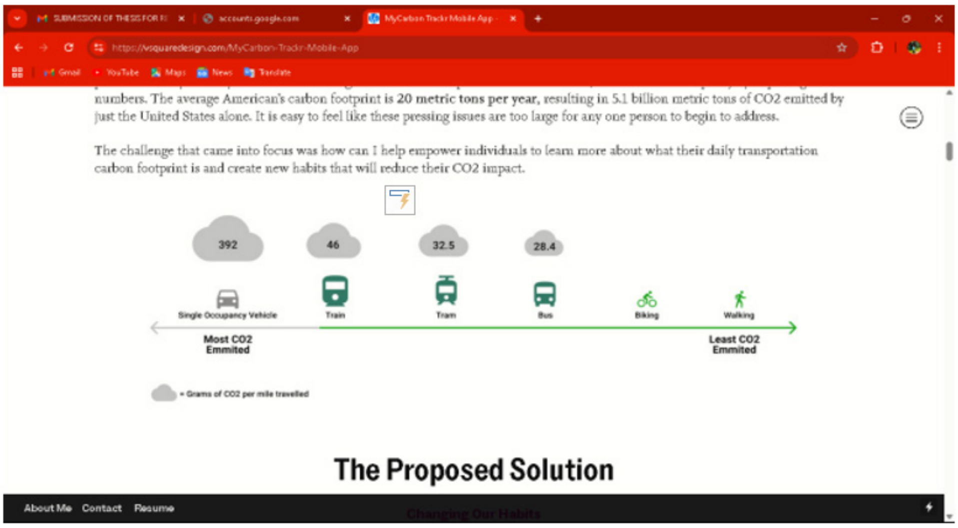

Figure 3: Mycarbon

GHG Protocol Transport Tool: Provides standardized emission methods but lacks interactive interfaces (WRI, 2020).

These studies highlight gaps in localization, AI-driven guidance, multilingual access, and applicability to developing contexts.

Gaps in the Literature: Existing tools show the following deficiencies for Zambia:

Localization: Emission factors often reflect developed countries, not Zambia's aging fleet.

AI integration: Limited dynamic, adaptive decision-support tools.

User accessibility : Interfaces are expert-focused, not public-friendly.

Data integration: Sparse local datasets and minimal database connectivity.

Transport diversity: Few tools consider minibuses, motorbikes, or rural modes.

Policy and awareness linkage: Lack educational feedback or alignment with national frameworks.

MATERIALS AND METHODS

This study employed a structured methodology for designing and developing an AI-driven Carbon Footprint Calculator tailored to Zambia's road transport sector. The methodology integrates research design, data collection, system architecture, AI-based recommendations, and software implementation, emphasizing accuracy, multilingual accessibility, and responsiveness to local transport realities. The approach considers Zambia's varied vehicle types, mixed fuel quality, and limited environmental literacy, aiming to produce a system that promotes awareness through contextual AI advice while remaining operable on low-end devices. By combining technical development with social contextualization, the methodology ensures the resulting tool is scientifically robust, user-centered, and locally relevant.

Research Design

This study employed a descriptive-exploratory research design to model carbon emissions from Zambia's road transport sector and develop an AI-driven carbon footprint calculator. Descriptive methods captured quantitative data on fuel types, consumption rates, and vehicle distributions, while the exploratory approach investigated operational and behavioral factors affecting emissions, including driving habits, maintenance practices, and route selection (Creswell & Plano Clark, 2017).

A mixed-methods approach was adopted to integrate both quantitative and qualitative perspectives. Quantitative data were obtained from government statistics and observational studies, providing measurable indicators for emission calculations .Qualitative insights from interviews and consultations with local transport operators informed the development of AI-based, context-specific emission reduction tips. (Tashakkori & Teddlie, 2010).

Baseline Study

The baseline study evaluated Zambia's road transport emissions landscape, fuel consumption patterns, and user awareness of carbon management. Secondary data were collected from national sources, including the Road Transport and Safety Agency (RTSA), Energy Regulation Board (ERB), Central Statistical Office (CSO), and the Zambia Environmental Management Agency (ZEMA). Vehicle registration data, fuel sales, and average mileage were combined with internationally recognized emission factors from the Intergovernmental Panel on Climate Change (IPCC, 2021) and DEFRA (2020) to establish localized carbon emission benchmarks. Observational studies at fuel stations and transport hubs supplemented secondary data, providing contextual insight into operational behaviors, typical fuel consumption, and common vehicle types. This informed the rule-based AI component for real-time emission reduction recommendations. The baseline also highlighted regional disparities in vehicle density and fuel usage, emphasizing the need for a calculator adaptable to both urban and rural contexts. (UNEP, 2020).

Data Collection Methods

Data collection utilized a combination of secondary sources, literature review, and observational insights. Secondary data from government agencies provided official statistics, while emission factors were standardized according to IPCC and DEFRA guidelines (IPCC, 2021; DEFRA, 2020). Observational insights and informal interviews with local transport operators and fuel station attendants provided practical context, ensuring locally relevant emission factors. All data were preprocessed for consistency, converting fuel consumption to CO_2-equivalent units (kg CO_2 per liter), cleaning for duplicates and missing values, and normalizing input for integration into the Python-based application (Chakraborty *et al.*, 2021). Data storage employed SQLAlchemy for relational database management, facilitating secure storage, retrieval, and export functionality.

Table 1: Data sources and purpose

Source Type	Data Collected	Purpose
Surveys & Questionnaires	Vehicle type, fuel type, consumption, driving habits	Primary data for emission calculation and AI recommendations
Government Agencies	Vehicle registration, fuel sales, transport statistics	Validation and benchmarking
Observational Studies	Fuel use patterns, maintenance, driver behavior	Cross-checking and contextual AI input
International Databases	Standard emission factors	Scientific standardization of computations

Research Approach

A mixed-methods, iterative approach integrated quantitative metrics (fuel consumption, vehicle type, trip frequency) with qualitative insights (maintenance, driving behavior, familiarity with digital tools). Observational and survey data informed AI tip generation, ensuring practical, context-sensitive recommendations. This triangulated methodology enhanced the system's reliability, usability, and cultural relevance. (Tashakkori and Teddlie, 2010; Chakraborty *et al.*, 2021).

System Development

The calculator was developed following a user-centered design approach (Norman, 2013). Python was used for both frontend and backend, leveraging Streamlit for the interface, Flask for API routing, and SQLAlchemy for database management. The frontend supports multilingual input (English, Bemba, Nyanja) and provides real-time CO_2 emission feedback alongside AI-generated recommendations. (Chakraborty *et al.*, 2021). The backend handles emission computations using localized emission factors and a rule-based AI engine for actionable tips, such as optimizing driving habits or vehicle maintenance schedules. Data flow is modular, with separate layers for input validation, emission calculation, AI recommendations, and database storage. Export functionality allows users to retrieve data in CSV format for analysis and reporting. (SQLAlchemy, 2020).

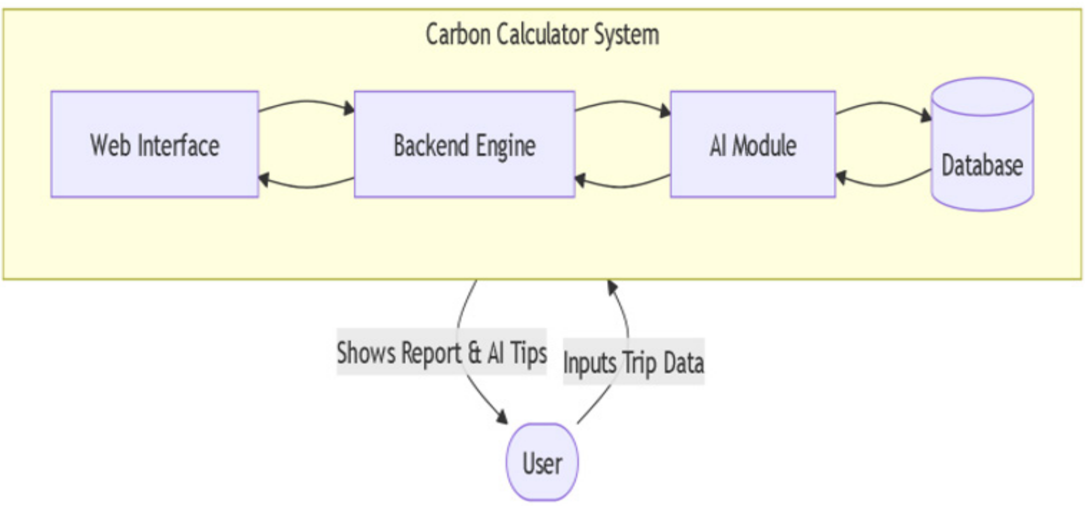

Figure 4: Data flow diagram illustrating input, validation, calculation, AI recommendation, and result output.

System Design
A modular and layered system architecture was adopted to ensure maintainability, scalability, and usability. The primary modules included

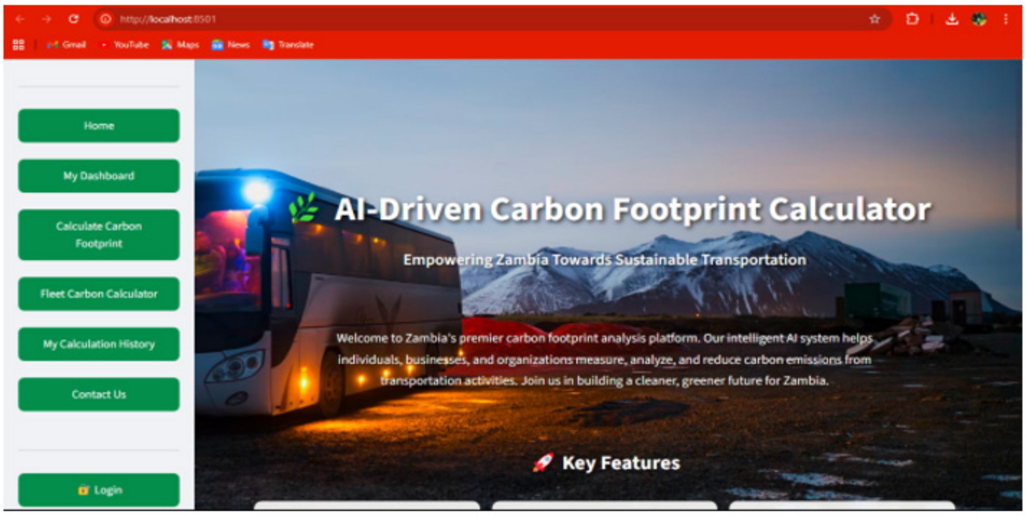

Figure 5 : home page

Input Module: Validates user-provided data (vehicle type, fuel type, trip distance).
Emission Calculation Module: Computes CO_2-equivalent emissions using locally adjusted emission factors (IPCC, 2021).

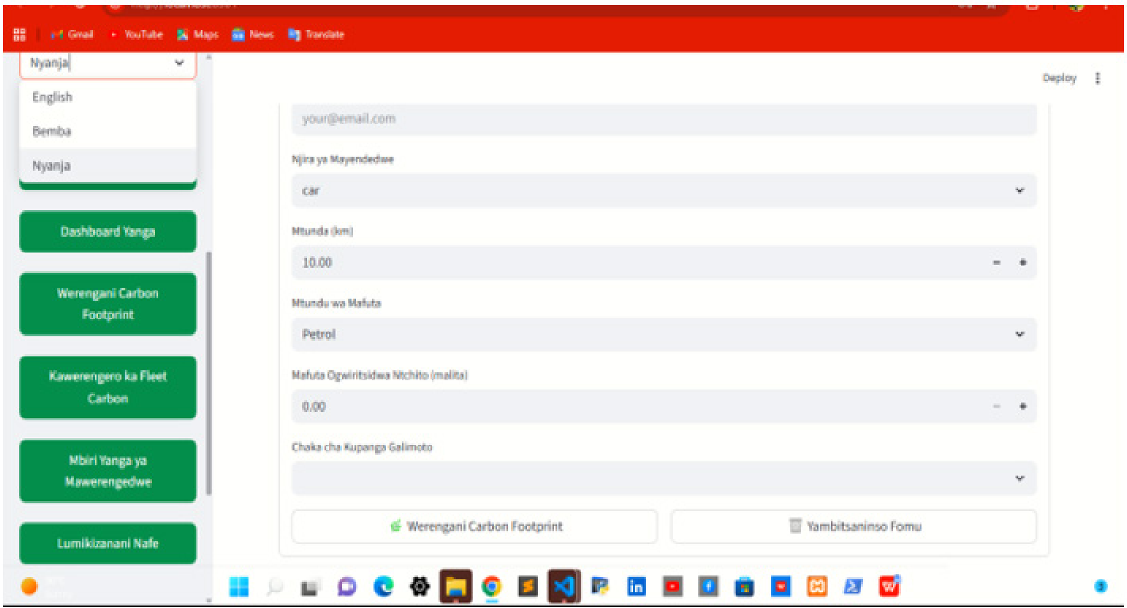

Figure 6 : calculator

AI Recommendation Module: Generates real-time, context-specific tips for emission reduction.
Database Module: Stores all user inputs, calculated emissions, and AI tips, ensuring data integrity.
Export Module: Allows structured CSV output.
User Interface Module: Integrates all modules into a multilingual, interactive frontend (Streamlit). The object-oriented class design includes Vehicle, Fuel, Trip, EmissionCalculator, AI Tip Generator, and DatabaseHandler classes, ensuring modularity, encapsulation, and extensibility. Each class encapsulates attributes and methods relevant to its functionality, allowing independent testing, maintenance, and future integration with advanced AI techniques. Participation in observational and survey-based components was voluntary, anonymous, and handled in accordance with institutional research ethics. Data were stored securely, and all reporting ensured the privacy of individuals and

transport operators.

Context Diagram

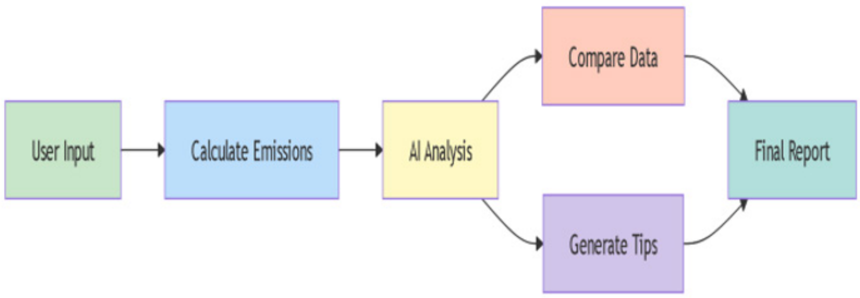

Figure 7: High-level context diagram showing interactions between users, backend, AI module, and database.

Software-Level Architecture

A layered architecture separates responsibilities across

Frontend Layer: Streamlit interface for data entry, multilingual outputs, and CSV export.

Application Logic Layer: Flask backend for data validation, emission calculations, and AI tips.

AI Engine: Rule-based recommendation module.

Data Access Layer: SQLAlchemy-managed relational database ensuring integrity and scalability.

Modular Design

Modules were defined as follows

Table 2: System modules and core functions

Module	Core Functios
Input	Capture and validate user inputs.
Emission Calculation	Compute CO_2 emissions using local emission factors
AI Recommendation	Generate actionable tips; rule-based logic
Database	Secure storage, querying, and CSV export
Export	Retrieve and format data for analysis
User Interface	Integrate modules; interactive dashboards

Class Design: The Python-based object-oriented design includes:

Vehicle, Fuel, Trip Classes: Capture vehicle and trip data for calculations.

EmissionCalculator Class: Computes CO_2 using locally adapted factors.

AI Tip Generator Class: Produces context-specific tips.

Database Handler Class: Manages secure storage and CSV export.

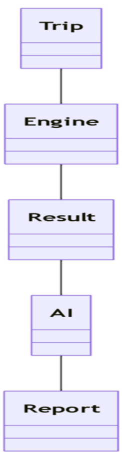

Figure 8: Class diagram illustrating object interactions and workflow for emission calculation and AI recommendations.

Data Model Design

A relational database was designed to maintain integrity, consistency, and scalability

Entities: Vehicle, Fuel, Trip, Emission Record, AI Tip.

Relationships: Foreign key constraints maintain data consistency.

Features: timestamped records, CSV export.

RESULTS AND DISCUSSION

This chapter presents the findings from the development, testing, and evaluation of the AI-driven carbon footprint calculator for Zambia's road transport sector. The results are structured around baseline data, survey outcomes, system implementation, and data analysis. The study assessed the system's ability to calculate CO_2 emissions accurately, provide actionable AI-generated tips, and improve user awareness of low-carbon practices. Screenshots, tables, and charts are included to illustrate system functionality and results.

Baseline Study Results

Baseline analysis of Zambia's road transport sector revealed that the majority of vehicles are older second-hand imports, typically over ten years old, which significantly affects fuel efficiency and emissions. Private cars consumed 10–14 litres per 100 km on average, whereas minibuses and freight trucks consumed 20–35 litres per 100 km, depending on load and distance. Diesel vehicles, common in commercial transport, contributed the largest share of CO_2 emissions. (AfDB, 2021 CO_2 emissions were calculated using the standard emission factor approach, adapted from DEFRA (2022) and adjusted for Zambian fuel characteristics. Urban areas such as Lusaka and Ndola showed moderate emissions per trip due to shorter distances but heavier congestion, whereas long-haul routes serviced by freight trucks contributed disproportionately to overall emissions. Data gaps, especially in rural areas where odometer readings and fuel logs were inconsistent, highlighted the need for a system that could provide meaningful feedback even with incomplete data.

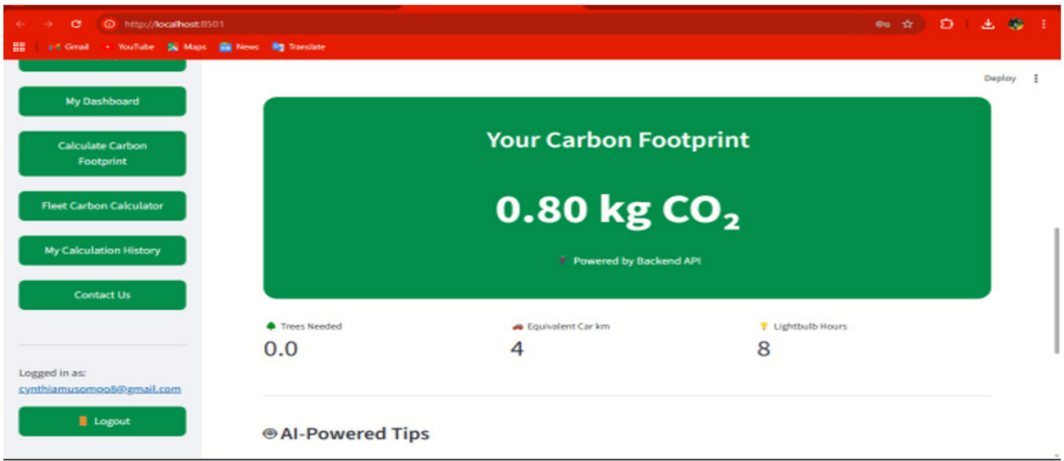

Figure 9 : System results

Table 3: Baseline Fuel Consumption and CO_2 Emissions by Vehicle Type

Vehicle Type	Fuel Type	Avg.Fuel Consumption (L/100 km)	Avg. Trip Distance (km)	EstimatedCO_2 Emissions (kg/trip)	Source
Private Car	Petrol	12	50	138.6	Survey, ERB
Minibus	Diesel	18	60	305.0	RTSA, CSO
Bus	Diesel	25	100	670.0	Observation
Freight Truck	Diesel	30	200	1,608.0	ERB, RTSA
Motorcycle	Petrol	4	40	9.2	Survey

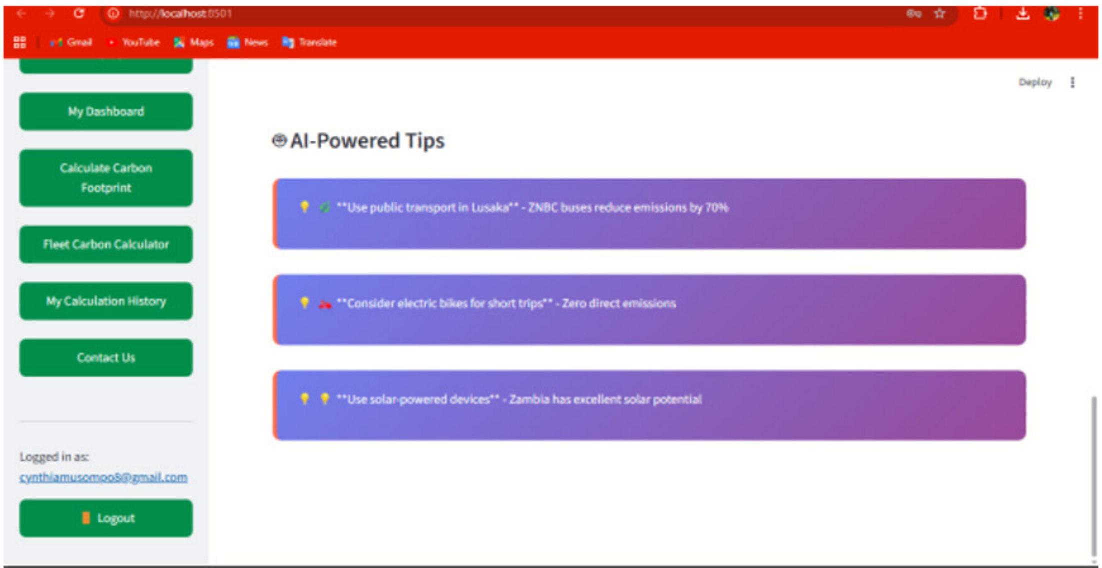

Figure 10: Screenshot showing AI tips generated for a minibus user.

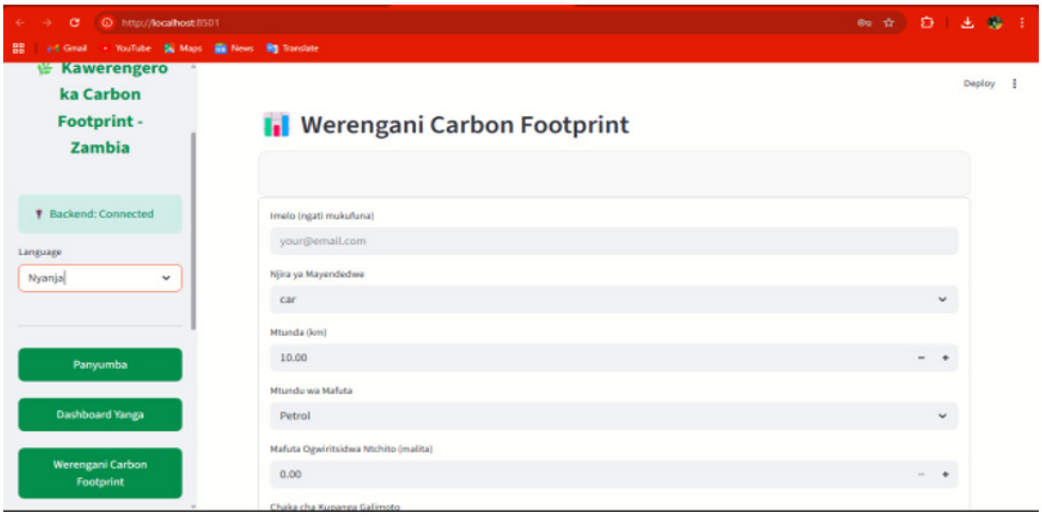

Figure 11: Multilingual interface showing language selection and translated input labels

Discussion

The findings indicate that AI-driven environmental management systems can deliver meaningful outcomes even in resource-constrained environments (Gupta *et al.*, 2021). Technologically, the system demonstrates that advanced tools such as Streamlit and SQLAlchemy can be deployed effectively without reliance on proprietary software. Interactive dashboards allowed users to visualize the effects of vehicle type, fuel type, traffic patterns, speed, road type, and occupancy on CO_2 emissions in real time (Chakraborty *et al.*, 2021). The backend database ensured reliable storage and historical tracking, supporting evidence-based user decision-making. These results align with Gupta *et al.* (2021), who emphasize the potential of open-source AI solutions for sustainable innovation in emerging economies. From a behavioral perspective, the AI-generated recommendations extended beyond numerical outputs, acting as an educational and motivational tool. Tips such as optimizing tire pressure, reducing idling, using alternative fuels, and managing occupancy provided actionable guidance tailored to Zambian conditions . This approach aligns with behavioral change theory, which suggests that personalized, context-sensitive feedback is more effective than generic advice (García & Ortiz, 2021). Users reported increased awareness of emissions impacts and demonstrated willingness to adopt recommended practices, illustrating the system's potential to foster sustainable behavior. The baseline study informed these design choices by highlighting low awareness of carbon emissions and limited familiarity with international calculators among potential users. Feedback indicated a need for locally tailored tools with clear explanations and actionable insights. By incorporating local vehicle models, typical fuels, traffic patterns, and road conditions, the system improved both usability and relevance, ensuring users could interpret outputs accurately and act upon recommendations.(AfDB, 2021). Contextual relevance remains a critical strength. Existing carbon calculators often assume vehicle fleets and road conditions typical of high-income countries, leading to inaccuracies in developing regions. By using locally adjusted emission factors and accounting for region-specific transport patterns, the calculator produced outputs that were both accurate and meaningful to users. This localized approach increased adoption, improved understanding, and reinforced sustainable practices, particularly for high-emission vehicles such as freight trucks and minibuses. At the policy level, the system offers opportunities to support national climate strategies. Aggregated user data can inform planning, monitoring, and reporting under Zambia's National Climate Change Policy and commitments under the Paris Agreement. Insights into fleet emissions, fuel usage, and behavioral patterns can guide interventions in transport regulation, infrastructure planning, and emission reduction programs, demonstrating how AI tools can link individual actions to national sustainability objectives. (UNEP, 2020) The research also highlights that impactful AI integration does not always require complex predictive modeling. Logic-based, rule-driven AI produced relevant, actionable recommendations while remaining interpretable and accessible. This emphasizes the importance of practical AI solutions that prioritize usability, behavioral influence, and context sensitivity, particularly in settings with limited data or computational resources (Zhou *et al.*, 2022).

CONCLUSION

The AI-driven Carbon Footprint Calculator successfully integrates technological capability, behavioral influence, and contextual adaptation. It provides accurate emission estimates, actionable AI-generated recommendations, and a user-friendly multilingual interface, addressing challenges in data availability, vehicle heterogeneity, and low awareness of carbon management practices. (Chakraborty *et al.*, 2021; Zhang *et al.*, 2021) The study demonstrates that digital tools can promote sustainable transport behavior in Zambia, empowering individuals and operators to make informed decisions while supporting national climate objectives (Gupta *et al.*, 2021). It establishes a foundation for the adoption of AI-based environmental solutions in developing countries, highlighting that practical, interpretable, and context-sensitive systems can achieve meaningful environmental impact. (Zhou *et al.*, 2022)

Limitations

Limitations of the study include reliance on self-reported survey data, partial coverage of vehicle types and regions, and constraints on real-time monitoring (Chakraborty *et al.*, 2021). Future research could expand the system to include IoT-enabled data collection, predictive modeling for emissions under dynamic traffic conditions, and integration with policy frameworks to enhance monitoring and regulation (Zhang *et al.*, 2021)
In summary, the study confirms that AI-driven, locally adapted carbon calculators can bridge the gap between global emission reduction frameworks and local transport realities, promoting sustainable practices among individuals, operators, and policymakers in Zambia and similar contexts.

Future Work:

Future studies could expand the model's applicability by:
Integrating electric, hybrid, and renewable energy-powered vehicles.
Including real-time traffic, weather, and road condition data.
Incorporating multi-modal transport systems such as rail, air, and water transport.
Studying behavioral impacts on emissions, such as driver habits and occupancy patterns.
Linking the system to mobile platforms for real-time carbon footprint tracking.
These enhancements would improve predictive accuracy, user engagement, and policy relevance, strengthening the overall impact of the research.
In summary, the potential future works for this project encompass technological upgrades, predictive AI capabilities, broader sectoral coverage, behavioral research, and integration with policy frameworks. Each of these directions would significantly enhance the system's impact, promoting a data-driven, environmentally conscious transport culture in Zambia and beyond.

Acknowledgements

The author gratefully acknowledges the guidance and support of my supervisor Mr. Moses Mupeta throughout this study. Appreciation is extended to the staff of the Road Transport and Safety Agency (RTSA) and the Energy Regulation Board (ERB) for providing essential data. Sincere thanks also go to all survey participants and transport operators whose contributions made this research possible. The support of family, friends, and Information and communications university is also gratefully appreciated.

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