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SPECIAL ISSUE: CELEBRATING 20 YEARS OF GEOGRAPHY IN KADUNA STATE UNIVERSITY - ADVANCES AND FRONTIERS IN GEOGRAPHY

Smart Transportation System: Evaluating the Effectiveness of Smart Transportation Systems in Reducing Congestion and Emissions in Kaduna Metropolis, Nigeria

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ABSTRACT

Urban transportation in Nigeria faces critical challenges of traffic congestion and rising emissions, which undermine economic productivity, environmental health, and urban livability. This study explores the potential and the actual use of smart transportation technologies, including Internet of Things (IoT), Machine Learning (ML), and Geographic Information Systems (GIS), to mitigate these challenges, with a specific focus on Kaduna Metropolis. A comparative case study approach is employed, using Lagos and Enugu as benchmarks for both established and emerging smart mobility interventions. Data were drawn from traffic volume counts, Peak Hour Factor (PHF) analysis, pollution metrics, and a comprehensive review of peer-reviewed studies. GIS mapping visualized congestion hotspots, while a proposed ML model demonstrates the potential for real-time traffic prediction. Results indicate that Kaduna metropolis experiences severe traffic congestion, with an average PHF of 0.78 and CO2 concentrations exceeding World Health Organization (WHO) safety thresholds. Lagos shows moderate improvements through initiatives such as Bus Rapid Transit (BRT) and ride-hailing platforms, while Enugu faces episodic traffic congestion due to socio-political disruptions. Based on these findings, the study proposes a context-specific smart transportation framework for Kaduna, integrating IoT-enabled traffic sensors, ML-driven analytics, and GIS-based spatial planning. The findings have broader implications for urban transport policy, infrastructure development, and sustainable mobility strategies in Nigerian cities and comparable urban contexts across Africa.

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1 Introduction

Urban mobility has, in the past few years, emerged as a major challenge facing Nigerian cities, especially due to high population growth rates and urban sprawls as well as the poor development of transport infrastructure. The rate of urbanisation in Nigeria, which is beyond 52% at present (Baba, 2005), still surpasses the process of infrastructure, thus exerting an uneven burden on transport. The most obvious manifestation of this imbalance is the issue of urban congestion, which undermines economic efficiency and also threatens the health of the general populace due to an increase in vehicular emissions. A perfect illustration is the case of Kaduna, which is a large northern metropolitan area and is marked by dysfunctional traffic systems, a range of infrastructural shortages, and surging pollution (Abdullahi et al., 2024; Baba, 2025).

Congestion represents a long-term problem that is intricately linked to emission levels due to the correlation between idle traffic and greenhouse gas outputs, particularly CO_2 and NO_2 (Audu et al., 2018). Empirical evidence reveals that traffic stagnation has also amplified urban pollution, which worsens respiratory diseases and ecological degradation (Baba, 2025). Smart transportation can optimize urban mobility in terms of efficiency and sustainability by focusing on digital technologies, including Internet of Things (IoT) to supervise transportation in real-time, Machine Learning (ML) to conduct predictive analyses, and Geographic Information System (GIS) to design spatial plans (Farman et al., 2022).

Urban transport in Nigeria faces an emergency, and emerging technologies are proving to be the solution. IoT applications in traffic management enable the deployment of sensors for real-time data collection on vehicle counts, speed, and congestion levels (Farman et al., 2022). For example, Lagos has piloted traffic data platforms that inform route planning and congestion alerts, though coverage remains limited to major arteries (Udo & Rad, 2025). Traffic forecasting with ML models is becoming more common. Udo and Rad (2025) applied Decision Trees, Random Forest, and Gradient Boosting models on Ikorodu Road in Lagos, achieving significant accuracy in predicting traffic volumes based on historical data. Such models highlight the promise of pre-emptive traffic control that precludes traffic build-up before it can take place.

GIS plays the role of the essential platform of investigation of the traffic patterns and the measurement of the environmental contamination in our modern scholarly world. The study by Adedeji et al. (2016), for example, employs GIS to delineate the spatial distribution

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of traffic-related air pollutants in Ijebu-Ode, thereby elucidating the correlation between traffic density and pollutant concentration. Such results indicate the presence of definite geographical differences in pollution in the air and, therefore, allow the accurate spatial focus of actions to control them in traffic hotspots, which is why both traffic control and environmental-health can be optimised.

Smart transportation systems are the merger of digital technologies and transport infrastructure in cities, which are aimed at optimising traffic, improving the user experience of commuters, and minimising negative effects on the environment (Farman et al., 2022) The conceptual foundation rests on the integration of Internet of Things (IoT) for data collection, Machine Learning (ML) for predictive traffic modelling, and Geographic Information Systems (GIS) for spatial planning and analysis.

Lagos, Nigeria's commercial capital, has initiated smart mobility measures, including the BRT system, digital ride-hailing platforms like Gokada, and traffic data platforms (Udo & Rad, 2025; Babaleye & Greblikaite, 2021). Enugu, albeit smaller, presents unique congestion dynamics shaped by socio-political activities such as the "sit-at-home" directives (Chukwurah et al., 2025). In contrast, Kaduna's transportation ecosystem remains predominantly informal, unregulated, and technologically underdeveloped. This comparative deficiency underscores the necessity of an evaluative and prescriptive study focusing on smart transport applications in Kaduna, informed by lessons from Lagos and Enugu.

By situating Kaduna within a comparative urban analysis, this study contributes to the growing discourse on sustainable urban mobility in sub-Saharan Africa and offers practical policy and technological pathways for Nigerian cities navigating the complexities of urban growth and environmental sustainability. This gap informs our research focus: evaluating how IoT, ML, and GIS can be integrated within Kaduna's urban mobility planning to reduce congestion and emissions, drawing comparative lessons from Lagos and Enugu. This research addresses the following objectives: to assess the current state of traffic congestion and emissions in Kaduna, to compare mobility patterns and interventions in Lagos and Enugu, to evaluate the applicability of IoT, ML, and GIS in reducing congestion and emissions in Kaduna, and to propose a strategic smart transportation framework tailored to Kaduna's urban context.

2 Materials and Methods

2.1 Study Area

The primary focus of this study is Kaduna Metropolis, comprising the whole of Kaduna North and Kaduna South Local Government Areas, and parts of Chikun and Igabi Local Government Areas. Kaduna is the capital of Kaduna State, strategically located in north-central Nigeria. The study area lies between Latitude 10 26′ 00′′ to 10 38′ 00′′N of the equator and between Longitude 7 22′ 00′′ to 7 33′ 00′ E of the Greenwich Meridian. The primary focus of this study is Kaduna Metropolis, comprising Kaduna North and South Local Governments, part of Chikun, and Igabi Local Government (Fig. 1).

The metropolis is a commercial and administrative hub, with an estimated population of 1.6 million (NPC, 2023). Rapid urban growth, compounded by industrial expansion and increasing vehicle ownership, has intensified pressure on Kaduna's transportation system, leading to chronic traffic congestion and deteriorating air quality (Abdullahi et al., 2024; Baba, 2025).

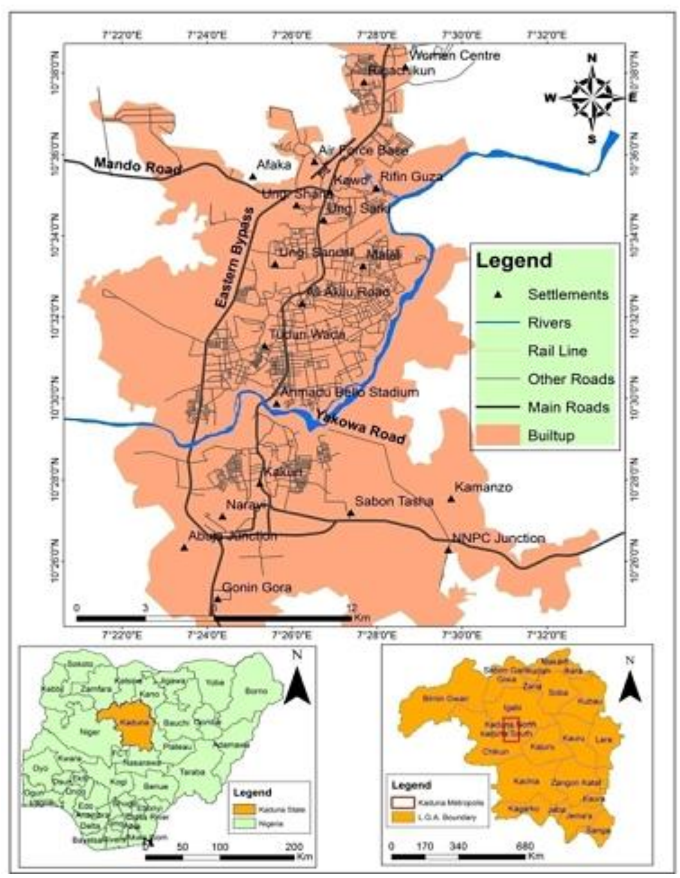

Figure 1: Map of Kaduna Metropolis Study Area

2.2 Comparative Cities

For comparative analysis, Lagos and Enugu (Fig. 2) were selected based on their urban mobility characteristics and existing smart transport interventions.

- Lagos: Nigeria's economic capital, with a population of over 20 million people, is the most developed Nigerian city regarding smart mobility practices. The most relevant projects are the Bus Rapid Transit (BRT) network, the implementation of the ride-hailing services, and the experimental traffic management systems (Babaleye & Greblikaite, 2021).

- Enugu: Enugu State Transport Company (ENTRACO) is the state-owned public transport company that operates buses for both intra-state and interstate travel, however, the company's fleet is often limited in capacity due to maintenance challenges, which leave room for private operators to fill the gap, which include the mini buses, *Danfo*, *Kabu-Kabu* and motorcycles Enugu is connected to other southern states like Anambra, Imo and Ebonyi. Major roads, such as Enugu-Port Harcourt Expressway, Enugu-Abakaliki Road, and the Enugu-Onitsha Road, are vital for long-distance intercity travel. Within the city, urban roads are often crowded and prone to traffic jams, especially around central locations like Ogui Road and Nike Lake Road. The state Government has also initiated modernizing the transport system, through improved infrastructure, such as road expansion projects and the introduction of Smart Transport System (STS), which include Integrated traffic management system like CCTV surveillance and real-time traffic monitoring, and also electronic ticketing and smart bus operation have been initiated, with vehicle tracking and management from ENTRACO. Public – Private Partnerships (PPPs) have also been initiated to improve the quality of services within the state.

Figure 2: Map of Nigeria, highlighting Kaduna, Lagos, and Enugu for Comparative Context

2.3 Data Sources

Traffic volume count was obtained from field observation and vehicle counts during peak hours across the major routes. The air quality data for CO_2, NO_2, and $PM_{2.5}$ in Kaduna State were obtained from the Copernicus Atmospheric Monitoring Service. While the GIS data and maps used were acquired from OpenStreet Map and analysed in ArcGIS 10.8. The data used and their sources are presented in Table 1.

Table 1: Data types and sources

Data Type	Source	Description
Traffic Volume Counts	Field observations in Kaduna	Vehicle counts during peak/off-peak hours across major routes
Peak Hour Factor (PHF)	Derived from traffic counts	Measures traffic congestion saturation levels
Air Quality Data	Baba (2025); Copernicus Atmospheric Monitoring Service	CO_2, NO_2, and $PM_{2.5}$ concentration levels in urban cores
GIS Data	OpenStreetMap, ArcGIS 10.8	Spatial data for mapping roads, congestion, and pollution hotspots
Secondary Data	Published literature	Traffic data from Lagos (Udo & Rad, 2025), Enugu (Chukwurah et al., 2025)

2.4 Data Collection

Traffic volume counts were conducted in Kaduna across major routes, which include Ahmadu Bello Way, Ali Akilu Road, Constitution Road, Tafawa Balewa Way, Independence Way, Waff Road, Shehu Laminu Road, Sultan Road, and Rabbah Road. These roads were selected because they are major roads within Kaduna metropolis linking residential, commercial, and schools for seven consecutive days, covering both morning (7:00 AM – 10:00 AM) and evening (4:00 PM – 7:00 PM) peak periods. Concurrently, air quality data were extracted for the same periods to assess pollution correlations with traffic density, acquired from the Copernicus atmospheric monitoring system.

Spatial data were obtained from OpenStreetMap and processed using ArcGIS (10.8) to visualise traffic congestion hotspots and overlay pollution data.

2.5 Data Analysis Methods

2.5.1 Peak Hour Factor (PHF)

The Peak Hour Factor (PHF) is a coefficient used in traffic engineering to account for fluctuations in traffic flow during an hour. It represents how consistently vehicles arrive at a specific point or intersection. A PHF closer to 1.00 indicates steady traffic flow, while a lower PHF suggests significant "peaking" or surges in traffic during a short interval. PHF was computed using Equation (1):

$$PHF = \frac{\textbf{Total hourly volume}\ (V)}{4 \times \textbf{Peak}\ V15}$$

Total Hourly volume (V): Total number of Vehicles recoded during a 60-minute period (vehicles per hour)

Peak 15-min volume (V_{15}): The highest number of vehicles observed during the single busiest 15-minute interval within that hour

The constant (4): Since there are four 15-minute periods in an hour, multiplying the peak interval by 4 converts the peak flow into an equivalent hourly rate.

2.5.2 GIS Spatial Analysis

Spatial analysis involved mapping congestion intensity and pollution hotspots using layered GIS techniques. This enabled visual identification of critical zones requiring intervention in Kaduna.

2.5.3 Machine Learning Predictive Framework (Adopted)

A predictive ML framework was conceptualised for potential deployment in Kaduna, and the Model validation will be achieved through a combination of data-driven performance evaluation, spatial comparison with observed impact pattern, review, and analysis drawn from Udo & Rad's (2025) Lagos study. Proposed algorithms include:

- Random Forest: For non-linear traffic predictions.
- Gradient Boosting: For enhanced prediction accuracy.
- Decision Trees: For interpretable traffic flow forecasts.

These models would require continuous data input from IoT-enabled sensors across Kaduna's transport corridors.

2.5.4 Proposed Model Training (Validation)

Data Sources for Training

The ML model should be trained using multi-source transport datasets, including:

i. Traffic flow data (vehicle counts, speeds, congestion levels).
ii. GPS and mobile phone data (travel time, route choice).
iii. Road network attributes (road class, width, intersections).
iv. Public transport data (bus routes, headways, ridership).
v. Socio-economic and land-use data (population density, employment centers).
vi. Weather and incident data (rainfall, accidents, road works)

2.5.5 Data Pre-processing

i. Data cleaning (outlier removal, missing value imputation).
ii. Temporal aggregation (e.g., 5-min, hourly, daily intervals).
iii. Feature engineering (peak/off-peak indicators, road centrality metrics).
iv. Normalization and encoding of categorical variables

2.5.6 Model Training Procedure

Split data into:

i. Training set (60–70%)
ii. Validation set (15–20%)
iii. Testing set (15–20%)

Algorithms commonly used:

i. Random Forest
ii. Gradient Boosting (XGBoost, LightGBM)
iii. LSTM / GRU (for time-series traffic prediction)
iv. Graph Neural Networks (for network-based transport models)
v. Hyperparameter tuning using grid search or Bayesian optimization

2.5.7 Model Validation Approaches

Validation demonstrates that the model is accurate, reliable, and generalizable.

Statistical Validation

Use performance metrics aligned with the model objective:

Task	**Validation Metrics**
Traffic volume prediction	RMSE, MAE, R^2
Travel time prediction	MAPE, RMSE
Congestion classification	Accuracy, Precision, Recall, F1-score
Mode choice prediction	Log-likelihood, ROC-AUC

A model is considered valid if it outperforms baseline models (e.g., historical averages or linear regression).

Cross-Validation

i. Apply k-fold cross-validation (k = 5 or 10)
ii. Ensures model robustness across different data subsets

iii. Especially important when datasets are small or noisy

Temporal Validation

i. Train the model on historical data
ii. Test it on future unseen periods
iii. Confirms predictive stability over time (crucial for transport planning)

Spatial Validation

i. Train the model using data from some corridors or zones
ii. Test it on other parts of the city
iii. Demonstrates transferability across urban areas

2.5.8 Pilot Testing (Real-World Validation)

i. Pilot testing shows practical applicability, not just statistical accuracy.

Pilot Area Selection

Select:

i. 1–3 major corridors
ii. Central Business District (CBD)
iii. High-congestion intersections

Example:
A pilot implementation can be conducted along Ahmadu Bello Way, which experiences recurrent congestion.

Pilot Deployment Process

Deploy the trained model in decision-support mode
Generate: Traffic predictions; Signal timing recommendations; Route diversion suggestions
Compare: Model recommendations vs existing traffic control strategies

Before-and-After Evaluation

Measure changes in: Average travel time, Queue length, Delay per vehicle, Fuel consumption and emissions, and User satisfaction (via surveys)
Statistical tests (e.g., paired t-test or Wilcoxon test) can confirm whether improvements are significant.

2.5.9 Institutional and Expert Validation

Stakeholder Review: Transport planners; Traffic police; Urban planners; Ministry of Transport officials
Experts assess: Practical feasibility; Policy relevance; Institutional compatibility

Scenario Testing

Test the model under: Peak vs off-peak hours, Rainy vs dry season, Road closure or accident scenarios. This demonstrates resilience and adaptability.

2.5.10 Model Retraining and Continuous Learning

Periodic retraining using: New traffic data; Updated land-use patterns; Online learning or rolling-window updates; Prevents model performance degradation over time.

In a nutshell, the model can be validated using statistical performance metrics, k-fold cross-validation, and temporal hold-out testing. A pilot implementation can further be conducted on selected urban corridors, where model outputs are evaluated against real-world traffic performance indicators, ensuring both technical robustness and practical applicability.

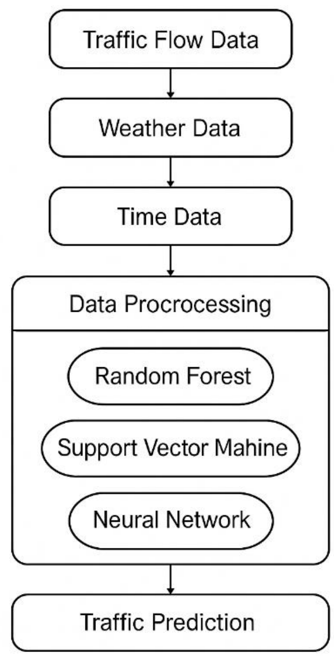

Figure 3: Proposed ML Architecture for Traffic Prediction in Kaduna

2.5.11 Comparative Policy Analysis

A qualitative assessment was undertaken to compare transport policies, smart mobility implementations, and technological readiness across Kaduna, Lagos, and Enugu, using data from Sumaila (2013), Kolo et al. (2021), and relevant local government documents.

2.5.12 Ethical Considerations

All traffic and environmental data utilised were derived from publicly available sources or existing studies with appropriate academic referencing. Field data collection adhered to ethical standards, ensuring non-intrusive observational methods.

3 Results

3.1 Traffic Congestion Patterns in Kaduna

The PHF values across key Kaduna routes (Nnamdi Azikiwe Expressway, Kawo Market, Ahmadu Bello Way) averaged 0.78 (Table 2), indicating significant congestion during peak hours. Weekday mornings showed the highest congestion intensity, correlating with commuting patterns towards administrative and commercial hubs.

Table 2: PHF Values Across Major Kaduna Routes

Route	Peak Hour Factor (PHF) Value
Nnamdi Azikiwe Expressway	0.81
Kawo Market Area	0.76
Ahmadu Bello Way	0.77

In comparison, Lagos exhibits higher congestion saturation than Kaduna, with Peak Hour Factor (PHF) values ranging between 0.82 and 0.88 on Ikorodu Road, one of the city's most critical transport corridors (Udo & Rad, 2025). This range indicates heavy traffic density, particularly during morning and evening rush hours. However, the implementation of the Bus Rapid Transit (BRT) system along designated routes has provided some relief, moderating congestion levels on those specific corridors. The BRT system, supplemented by ride-hailing services such as Gokada and digital traffic platforms, has created partial modal shifts from private vehicle use to public transport, albeit not at a scale sufficient to significantly reduce overall PHF across the city (Babaleye & Greblikaite, 2021).

In Enugu, the PHF analysis indicates a peak value of 0.75, reflecting moderate congestion intensity when compared to Kaduna and Lagos (Chukwurah et al., 2025). Nonetheless, this moderate intensity is coupled with decreased stability and increased sensitivity toward week-level socio-political processes, primarily the sit-at-home protests and curfews imposed across the southeast region. These situations do cause exaggeratedly large shifts in traffic volumes: traffic volumes shrink drastically on days when enforced idleness leads to the creation of a slack demand, followed by exaggeratedly large rebound effects as residents congregate once more to regain lost economic and social activity. Unlike the episodic peak-and-valley trend of Enugu, Kaduna portrays a more consistent daily congestion trend with more consistent workday-centered patterns.

Overall, these comparative PHF values not only quantify congestion severity but also reveal how institutional interventions (such as BRT in Lagos) and socio-political dynamics (such as in Enugu) shape urban traffic conditions in Nigeria's cities. Kaduna, lacking such structured interventions or unique socio-political disruptors, experiences persistent congestion driven primarily by infrastructural deficits and unregulated transport systems.

3.2 Emissions Profile

Kaduna's average CO_2 concentration stood at 415 ppm (Table 3), exceeding the WHO's recommended maximum of 400 ppm. NO_2 levels averaged 45 μg/m³, while $PM_{2.5}$ concentrations reached 38 μg/m³, both surpassing safe thresholds (Baba, 2025).

Table 3: Comparative Air Quality Indicators – Kaduna, Lagos, Enugu

City	CO_2 (ppm)	NO_2 (μg/m³)	$PM_{2.5}$ (μg/m³)
Kaduna	415	45	38
Lagos	420	50	40
Enugu	410	42	35

3.3 Spatial Mapping

GIS analysis highlighted the concentration of congestion and emissions around Nnamdi Azikiwe Expressway, Kawo Market, and Kaduna Central Business District. The result is shown in Figs. 4 and 5.

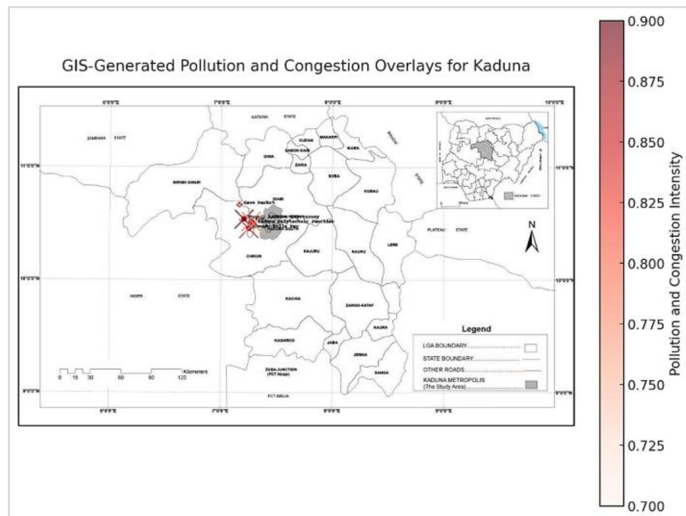

Figure 4: GIS-Generated Pollution and Congestion Overlays for Kaduna

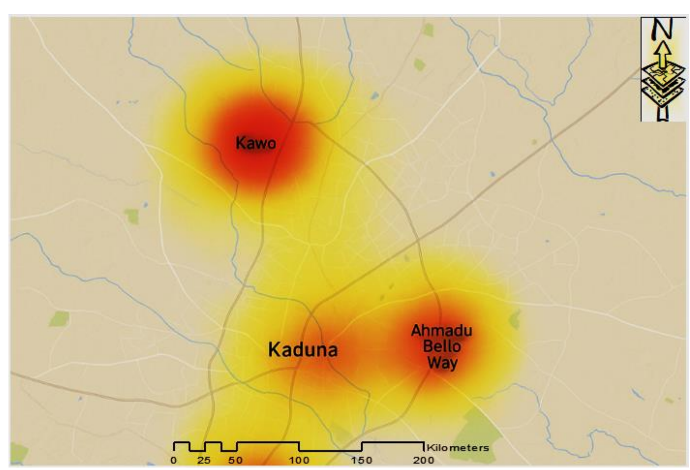

Figure 5: GIS-Generated Heatmap of Kaduna Showing Traffic Congestion Hotspots

4 DISCUSSION

As the data indicate, the issue of traffic jams and emissions is systemic in the context of Nigerian cities, though with unique trends, levels, and the nature of the cause in Kaduna, Lagos, and Enugu. This section represents a critical interpretation of those findings, tracing them to current scholarly discourses and assessing the promise of smart transportation technologies, namely IoT, ML, and GIS, as strategic interventions.

4.1 Kaduna's Transport Crisis: Manifestations and Structural Deficiencies

The 0.78 PHF that has been observed in the major corridors in Kaduna highlights the problem of chronic congestion, particularly in peak times of the week. This is consonant with findings by Abdullahi et al. (2024), who cited road obstructions, narrow carriageways, and encroachment of informal markets to worsen the situation. Moreover, Kaduna's road network remains underdeveloped, lacking sufficient bypasses and ring roads to disperse traffic effectively. In contrast to Lagos's BRT corridors, where congestion mitigation is partial due to dedicated lanes (Udo & Rad, 2025), Kaduna's public transport remains informal, dominated by tricycles and minibuses that lack coordination and regulation. This contributes to traffic indiscipline, erratic stops, and inefficient route usage, further inflating congestion levels.

4.2 Emissions: Kaduna's Environmental Vulnerability

Kaduna's urban core exhibits CO_2 concentrations averaging 415 ppm, surpassing the WHO safe threshold of 400 ppm (Baba, 2025). This pollution footprint is not merely a function of traffic density but also of the high prevalence of ageing vehicles with poor emission standards. Audu et al. (2018) similarly noted that Kaduna's air quality is adversely affected by unregulated vehicular emissions, industrial activities, and poor urban planning.

Comparatively, Lagos registers slightly higher CO_2 concentrations (420 ppm) but benefits marginally from policy-driven vehicle emissions testing, although implementation remains inconsistent (Oluwakoya, 2024). Enugu's emissions are comparatively lower, attributed to its smaller vehicular fleet and intermittent economic activities driven by socio-political disruptions (Chukwurah et al., 2025).

4.3 GIS and Spatial Understanding of Congestion

Geographic Information Systems (GIS) mapping is also central to the visualisation and analysis of spatial patterns of urban traffic congestion and pollution, as seen in Kaduna. The heatmap generated using the GIS in the paper indicates that the concentrations of congestion and pollution are geographically evident along the Nnamdi Azikiwe expressway, Kawo market, and the Central Business District (CBD). These areas are strategic economic and social high-activity areas that involve businesses, government administrative processes, and vehicle concentration, thus forming natural hot spots of congestion. This spatial concentration is not unique to Kaduna but reflects a broader trend documented in other urban studies. For example, Adedeji et al. (2016) employed GIS to map traffic-related air pollution in Ijebu-Ode, Nigeria, and similarly found that pollution concentrations and traffic congestion often overlap with commercial and administrative centres. This correlation between economic centrality and mobility bottlenecks underscores the complex geography of urban movement, where people, goods, and services gravitate toward high-density zones, exacerbating congestion and environmental pressures.

Spatial concentration of traffic has implications for planning interventions, including zoning policies, infrastructure upgrades, and targeted smart mobility deployments. GIS, therefore, not only visualises existing patterns but also guides evidence-based planning for traffic decongestion and pollution control.

4.4 Machine Learning and IoT Prospects for Kaduna

The ML models demonstrated by Udo and Rad (2025) on Ikorodu Road in Lagos present a viable template for Kaduna. Random Forest and Gradient Boosting algorithms achieved high predictive accuracy for traffic volumes, offering an anticipatory approach to congestion management. However, IoT-enabled sensors would also be required to collect real-time traffic data, which forms the bottom layer, which is not present in the ML model operation in Kaduna. The framework offered by Farman et al. (2022) on IoT traffic control in Pakistan does support the scalability of those systems in general, provided their localisation into local contexts. With the use of live data on the IoT-based sensors coupled with ML predictions, the city of Kaduna would be able to deploy dynamic traffic signal management, road adjustment, and congestion warnings, which would significantly ease the traffic and minimise the idle time of vehicles as they cause congestion and contribute to emissions.

By combining ML traffic forecasts with real-time data from IoT sensors, Kaduna could implement dynamic traffic signal control, adaptive route planning, and congestion alerts, substantially improving traffic flow and reducing vehicle idle times that contribute to emissions. The conceptual framework is illustrated in Fig. 6.

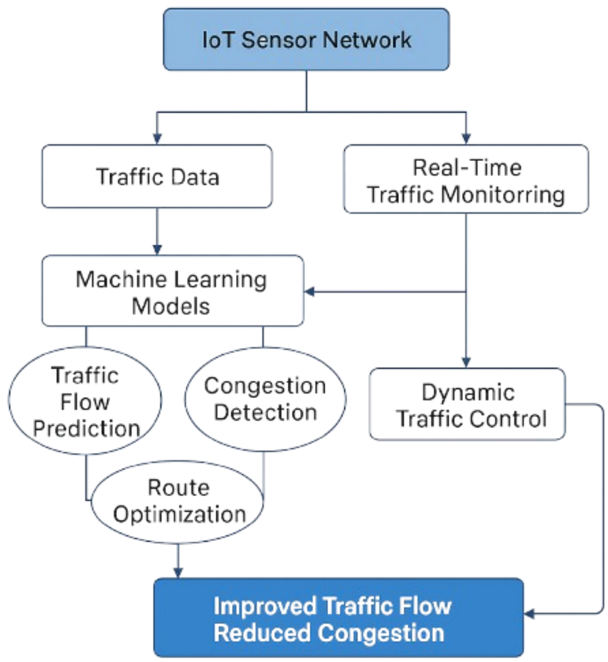

Figure 6: Conceptual Framework for IoT-ML Integrated Traffic Management in Kaduna

4.5 Policy and Institutional Challenges

Policy inertia remains a critical barrier in Kaduna. Sumaila (2013) and Kolo et al. (2021) emphasise that while Nigeria possesses a comprehensive National Transport Policy, its execution is hampered by poor governance, limited funding, and weak inter-agency coordination. Kaduna exemplifies this governance gap, lacking a dedicated smart transportation policy or institutional framework to support Intelligent Transportation System (ITS) deployment. In contrast, Lagos has made strides with state-level policies fostering public-private partnerships in transport innovations, yet challenges of sustainability and scalability persist. Enugu's transport policies remain ad hoc, with no strategic vision for smart mobility despite evident congestion trends (Chukwurah et al., 2025).

4.5.1 Fragmented and Overlapping Institutional Mandates: National–State Policy Disconnect

In Nigeria, transport governance is split across federal, state, and local authorities without clear alignment. Each level often has its own policies, sometimes contradictory or duplicative. This weakens coordinated planning and makes implementing integrated solutions like smart transportation systems more complex.

At the state level, Kaduna's transport agencies may lack the formal authority or defined role to implement certain digital standards (e.g., smart traffic controls, integrated payment systems) because national laws or policies do not empower them fully or uniformly.

4.5.2 Regulatory Overlap and Confusion

Nigeria's transport sector typically has multiple regulatory bodies with unclear responsibilities and conflicting mandates. Even if this has been documented at the national level, similar overlaps can occur within states where state transport ministries, traffic enforcement authorities, and local government transport units are not well-coordinated.

This institutional overlap blurs accountability and slows decision-making, a major hurdle for smart policy adoption that requires clear governance pathways.

4.5.3 Weak Institutional Capacity

Human and Technical Capacity Constraints

Many government agencies in Nigeria, including those managing transport, struggle with skill gaps, including expertise in digital systems, data analytics, transport modelling, and information technology that are core to smart mobility policy.

- Smart transport systems rely on:
- real-time data management,
- automated enforcement systems,
- integrated fare and payment platforms, and
- GIS/AI tools

Without trained professionals or continuous professional development programs, agencies struggle to design, implement, manage, and maintain such technologies.

Organisational Weaknesses

Other capacity issues include:
Low institutional memory due to frequent staff turnover,
Limited research capacity to assess complex transport needs and evaluate policies, and
Inadequate internal coordination mechanisms to manage cross-sectoral projects (for example, projects that require coordination with energy, urban planning, and ICT departments).
These weaken the institutional backbone necessary to steer smart transportation reforms.

4.5.4 Governance and Political Economy Barriers

Policy Instability and Political Transitions

Frequent changes in administration and leadership priorities, common in Nigerian state politics, can lead to shifts in policy emphasis, causing smart transport initiatives to lose momentum or funding. Projects initiated under one political leadership might be deprioritised under another, undermining continuity.

Weak Implementation and Enforcement

Even when policies exist, enforcement often falters due to corruption, weak accountability systems, and resource constraints. For example, Traffic rules may be poorly enforced, Data standards for digital systems might not be mandated, and financial and operational compliance is irregular. This weak governance undermines credibility and private sector confidence, which smart systems often require.

4.5.5 *Funding Mechanisms and Financial Limitations*

Insufficient Budget Allocations

Public funding for transport infrastructure, let alone smart technologies, is generally insufficient relative to needs across Nigerian states. Kaduna has some ambitious transport projects (e.g., the Kaduna Bus Rapid Transit) with significant counterpart funding, but such projects are exceptions rather than the norm and often depend on external partners. Smart transport requires: upfront investment in technologies (sensors, data platforms), ongoing operational expenditure, staff training, and maintenance budgets. Without adequate line-item budget allocations and ring-fenced funding, these cannot be sustained.

Limited Public-Private Partnership (PPP) Implementation

While PPP frameworks exist (e.g., Nigeria's Infrastructure Concession Regulatory Commission at the federal level), at the state level, legal and regulatory frameworks are weak or not fully implemented, making it difficult to attract private investment for smart transport initiatives. Barriers include: unclear revenue-sharing arrangements, limited legal protection for investors, weak mechanisms for performance monitoring, and low capacity to negotiate contracts. This results in reluctance from private firms to invest in digital systems like smart ticketing or transport analytics.

Dependence on Donor Funding

Many modern transport initiatives in Kaduna and other states are tied to external funding, such as partnerships with foreign development agencies. While useful, this can misalign priorities if donor mandates differ from local needs, and it can create dependency instead of sustainable local financing.

4.5.6 *Comparative Synthesis: Lessons for Kaduna*

From Lagos, Kaduna can learn the value of infrastructure-backed policy innovation, where BRT and ride-hailing platforms, despite limitations, offer incremental mobility improvements. Enugu's case teaches the importance of context-sensitive traffic management, adaptable to socio-political variables that can unpredictably alter mobility patterns.

Critically, the Kaduna context demands a holistic smart transportation framework, integrating:

- IoT sensors for data acquisition.
- ML algorithms for traffic forecasting.
- GIS platforms for spatial monitoring.
- Policy reforms fostering public-private collaborations and funding mechanisms.

This integrated approach aligns with Zhang et al.'s (2025) Meta City framework, which advocates data-driven governance for urban sustainability.

5 Conclusion

Kaduna's urban mobility is facing increasing pressure due to rising congestion and emissions, largely caused by outdated and inefficient traffic management systems. This study has shown that without meaningful intervention, the city risks deepening its mobility crisis, thus threatening urban sustainability, economic growth, and public health. Drawing insights from Lagos and Enugu, this study highlights that smart transport technologies, particularly the use of Internet of Things (IoT), Machine Learning (ML), and Geographic Information Systems (GIS), can significantly enhance traffic management and urban planning. Together, these technologies offer a powerful framework for transforming Kaduna's transportation landscape. However, their success is heavily dependent on the local context, including infrastructure readiness, institutional strength, and socio-political stability.

Accordingly, this study recommends that for Kaduna to successfully transition to a smart mobility system, technology must be supported by strong policy frameworks, strategic investments, and active public participation. Key actions include the development of a state-level smart mobility policy that sets standards for intelligent transport systems and data governance. Real-time traffic data should be collected through IoT sensors, while ML models trained on local data can help predict and manage congestion more effectively. A GIS-based monitoring system should support continuous tracking of traffic flow and emissions to inform planning decisions. In addition, Public-private partnerships involving government, academia, and the tech industry can drive innovation and ensure sustainable funding. At the same time, building the technical capacity of transport planners and policymakers will be crucial for implementing and managing these systems. Lastly, public awareness and citizen engagement must not be overlooked. Encouraging community involvement, particularly through mobile-based data reporting, can enhance the responsiveness and inclusiveness of the mobility system.

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