

# Enhancing Transportation Efficiency in Sokoto State Metropolis Through Vehicle Routing Problem Optimization

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## ABSTRACT

Enhancing transportation is critical to urban development, particularly in rapidly growing regions like Sokoto State in Nigeria. The Vehicle Routing Problem (VRP) is a widely researched optimization problem that seeks to find the most efficient routes for a fleet of vehicles to service a set of customers or locations, minimizing travel costs and time. This paper explores how Vehicle Routing Problem (VRP) optimization can address transportation challenges in the Sokoto metropolis by designing efficient routes for vehicle fleets. The study incorporates extensive data collection, including geospatial data on road networks, traffic patterns, population density, analysis, VRP model creation, optimization, and key points of interest, to customize VRP solutions to the unique characteristics of Sokoto. Results indicate significant potential for VRP optimization to reduce travel distances, lower operational costs, and contribute to environmental sustainability.

**Keywords:** Vehicle Routing Problem, Optimization, Transportation, Electric vehicle, Data.

## 1.0 INTRODUCTION

Urban centers in developing regions face unique transportation challenges due to rapid population growth and inadequate infrastructure. Sokoto metropolis, for instance, experiences significant traffic congestion, high operational costs, and delays caused by poor road quality. The Vehicle Routing Problem (VRP) is a mathematical optimization model designed to determine the most efficient routes for a fleet of vehicles, addressing a range of constraints such as vehicle capacity and time windows. Research has shown that VRP-based optimizations can reduce logistics costs by up to 30% in urban settings. However, existing literature frequently focuses on developed cities with robust infrastructure and real-time data systems, leaving a gap in understanding how VRP can be adapted to the specific constraints of developing cities like Sokoto.

The optimization of vehicle routing problems (VRP) in the context of transportation challenges in Nigeria has been the focus of several studies. Given the popularity of the subject of VRP optimization, there have been recent publications reviewing and discussing it.

Adeyemi and Ogunbode (2020) conducted a comprehensive review of urban transportation challenges and strategies in Nigerian cities. Although their study does not specifically address VRP optimization, it provides valuable insights into the broader transportation context in Nigeria. The authors highlight the limitations and inefficiencies in the existing transportation systems and discuss various strategies to address these challenges.

This review serves as a foundation for understanding the overall transportation landscape in Nigeria and the need for efficient and optimized vehicle routing systems. Altabebe *et.al.* (2019) investigated an improved Hybrid firefly algorithm for capacitated Vehicle Routing Problem. Lin *et.al.* (2019) studied an effective order-aware Hybrid genetic algorithm for Capacitated Vehicle Routing Problems in internet of things.

Akinbogun and Adeyemi (2019) investigated the effect of transportation infrastructure on economic development in Nigeria. While their study focuses on the broader economic impacts of transportation infrastructure, their findings have implications for VRP optimization. They emphasize the importance of developing robust transportation infrastructure to facilitate economic growth. This underscores the significance of optimizing vehicle routing systems as part of broader transportation infrastructure development initiatives. Mohammad *et.al.* (2021) presented a research paper on a novel algorithm for capacitated VRP for smart cities. Chipumuro *et. al.* (2014) studied the application of vehicle route optimization for improving distribution systems. A study on multi-objective capacitated Vehicle Routing for smart cities using NSGA-II optimization was carried out by Kotecha and Garg (2021).

Abdullahi and Tanimowo (2020) explored the relationship between transport infrastructure development and urbanization in Nigeria. Although their study does not directly address VRP optimization, it

sheds light on the importance of transportation infrastructure in accommodating rapid urbanization. Murray and Smith (2015) analyzed research on optimizing vehicle routing for efficient transportation in urban areas. As urban centers expand, the need for efficient and optimized vehicle routing becomes increasingly critical to mitigate congestion, reduce travel times, and improve overall transportation efficiency. Yan and Zhang (2016) presented a review and classification of Vehicle routing problems with time windows. Also, Rabbouch *et.al.* (2020) analyzed an empirical-type simulated annealing for solving the capacitated Vehicle Routing Problem, while Demir *et. al.* (2019) investigated a study on Vehicle Routing Problem: Past and Future.

With the advancement of Electric and Autonomous Vehicles (EAV), recent research has also addressed VRP in the context of green logistics. For example, Kellen *et. al.* (2023) reviewed the applications of VRP for EAVs, examining how route optimization can consider charging station locations, battery life, and energy consumption. Their findings emphasize the growing relevance of VRP in promoting environmentally sustainable urban logistics, aligning with Nigeria's objectives for sustainable development. Studies by Themistoklis *et. al.* (2023) and Ziago *et. al.* (2021) similarly discussed VRP models that incorporate nonlinear energy recharging and consumption, specifically tailored for electric vehicles. Zhao *et. al.* (2021) studied time-dependent electric vehicle routing problems with flexible time windows. Also, Saini and Saha (2021) conducted research on multi-objective optimization techniques: a survey of the state-of-the-art and applications. In another article, a comprehensive review of electric vehicle routing problems on variations and algorithms was investigated by Qin *et. al.* (2021) while Toth and Vigo (2014) analyzed vehicle routing problems, methods, and applications.

In terms of optimization techniques, De and Bhattacharya (2020) focused on the Green Vehicle Routing Problem (GVRP), a model that aims to minimize environmental impacts, such as fuel consumption and emissions, while optimizing routes. Although not specific to Nigeria, their work provides valuable insights into sustainability-oriented VRP models that are relevant for addressing environmental challenges in developing regions like Sokoto.

In the Nigerian context, Odumosu *et. al.* (2018) explored VRP applications for student transportation using a GIS and programming approach, while Solomon (1987) developed an algorithm for vehicle routing and scheduling problems with time window constraints.

Similarly, Salhi and Nagy (2019) reviewed an article on recent developments in vehicle routing. These studies provide foundational insights into VRP applications for diverse transportation needs within the country.

The study conducted by Keyong *et al.* (2021) systematically examined the existing articles on VRPs during the epidemic. Their focus was on the application of VRPs in controlling the spread of the pandemic, and numerous themes emerged: efficient pharmaceutical delivery, contactless distribution, sustainable waste transportation, and isolated and quarantined vehicle scheduling.

Building on these studies, our research seeks to adapt VRP to the infrastructure limitations of the Sokoto metropolis and develop a systematic, data-driven framework for optimizing transportation in developing cities. By applying dynamic programming techniques to analyze the Nigerian road network, this study aims to redesign and improve route efficiency, offering a sophisticated approach to vehicle routing within Sokoto. Our work thus represents a step forward in addressing transportation efficiency and operational costs in developing urban centers, laying the groundwork for broader VRP applications in similar regions.

All these works contribute perspectives on VRP, transportation infrastructure, or green vehicle routing, providing a foundation for understanding transportation challenges and VRP applications relevant to Sokoto State.

This study is regarded as a noteworthy contribution that has inspired our research efforts. It has served as the foundation for designing and implementing a model system for optimizing terminals and vehicle routing within the Sokoto metropolis.

## 2.0 CURRENT TRANSPORTATION CHALLENGES IN SOKOTO STATE

Key transportation challenges in Sokoto include:

- i. **Inadequate Road Infrastructure:** Poor road conditions hinder smooth travel and increase vehicle maintenance costs.
- ii. **Congestion:** Frequent bottlenecks, especially in commercial and high-density residential areas, lead to delays.
- iii. **High Fuel Costs and Emissions:** Inefficient routing contributes to elevated fuel consumption and emissions.
- iv. **Limited Data Availability:** Sparse traffic monitoring infrastructure complicates route planning and optimization.

### 3.0 METHODOLOGY

To address transportation efficiency in Sokoto metropolis using Vehicle Routing Problem (VRP) optimization, the methodology for this research follows a systematic approach encompassing data collection, analysis, VRP model creation, optimization, model analysis, and comparison with existing transportation methods.

#### 3.1 Systematic Approach to Address Transportation Challenges

The methodology begins with identifying Sokoto's transportation inefficiencies and formulating research objectives based on VRP optimization. By focusing on areas with high traffic congestion and poor road conditions, we aim to optimize routes that consider local constraints.

#### 3.2 Data Collection

The following data was collected to model Sokoto's urban transportation:

- i. **Geospatial Data:** Geographic Information System (GIS) data was collected to map Sokoto's road network, including road quality, intersections, and road length.
- ii. **Traffic Patterns:** Data was gathered on characteristics of goods transportation, such as traffic volume frequency during peak and off-peak hours, especially at major intersections and from available governmental and public sources.
- iii. **Population Density and Points of Interest (POI):** By mapping areas with high population density and significant POIs, such as schools, hospitals, and marketplaces, we targeted areas likely to impact delivery demand and congestion.
- iv. **Vehicle Fleet Information:** Gather Information on the existing transportation system, including public vehicle types, capacities, speeds, and operational costs (e.g., fuel consumption).

#### 3.3 Data Analysis

Using spatial analysis tools and traffic data modeling, we examined congestion levels, road conditions, and travel speeds. Population density data was correlated with traffic patterns to prioritize routes that serve densely populated areas.

#### 3.4 Model Creation using Vehicle Routing Problem Optimization (VRP)

**VRP Model Formulation:** A Capacitated VRP (CVRP) model was developed, incorporating vehicle capacity, time constraints, and the varying road quality across Sokoto. We adapted the VRPTW (VRP with Time

Windows) model to account for peak traffic conditions, ensuring the model reflects real-world constraints. The VRP was formulated with the following mathematical components:

- i. **Objective Function:** Minimize the total distance traveled by vehicles while ensuring demand fulfillment.

$$\min \sum_{i=1}^n \sum_{j=1}^n c_{ij} x_{ij}$$

where:

$$x_{ij} = 1 \text{ if a vehicle travels from node } i \text{ to } j \\ \text{otherwise } 0$$

$c_{ij} = 1$  represents the travel constant. (eg distance or time) between nodes  $i$  to  $j$

- ii. **Constraints:**
- iii. **Capacity Constraint:** Each vehicle must respect its load capacity  $Q$ .

$$\sum_{i=1}^n d_i x_{i,j} \leq Q$$

Where  $d_i$  is the element at each node  $i$ .

- iv. **Time Windows (if applicable):** Specifies service times at nodes, useful during peak traffic hours.
- v. **Demand Fulfillment:** All demand points in Sokoto must be served.
- vi. **Return to Depot:** Each vehicle must return to the starting point.

#### 3.5 Optimization Algorithm

We used a hybrid Genetic Algorithm (GA) and a Simulated Annealing (SA) approach to solve the VRP. GA explores potential route configurations, while SA refines promising routes, achieving a balance between exploration and exploitation.

- i. **Genetic Algorithm (GA):** Generating a diverse set of initial routes fosters a wide solution search.
- ii. **Simulated Annealing (SA):** Applied for local optimization, refining routes generated by GA to reduce total travel distance further.

#### 3.6 Model Analysis

The model's effectiveness was evaluated using several metrics:

- i. **Travel Time Reduction:** By comparing optimized routes to existing ones, we measured the reduction in travel time and its impact on delivery efficiency.
- ii. **Cost Savings:** Operational cost savings were calculated based on reductions in fuel usage, vehicle wear, and maintenance costs.

- iii. **Environmental Impact:** Emission reductions were assessed by comparing fuel consumption between the optimized and non-optimized routes.

### 3.7 Comparison with Existing Transportation Methods

To gauge the VRP model's impact, we compared it with existing transportation practices:

- i. **Current Routing Practices:** We analyzed current routes based on anecdotal evidence and observed delivery patterns from local operators.
- ii. **Performance Metrics:** The optimized model's performance was assessed relative to baseline metrics, such as travel times, costs, and emissions, allowing a direct comparison with existing transportation methods.

After optimization, the results were analyzed through metrics such as reduced travel distance, travel time, and operational costs.

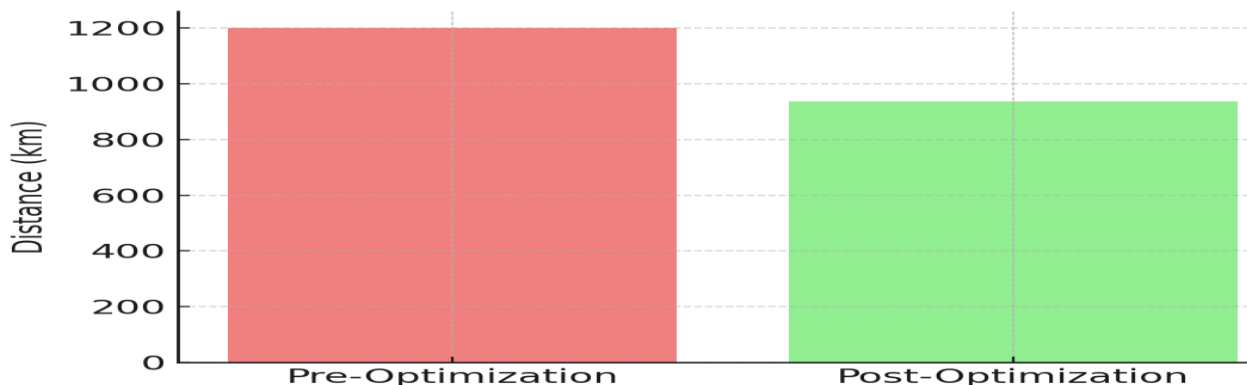
## 4.0 RESULTS AND DISCUSSION

The VRP optimization model demonstrated substantial improvements in Sokoto's transportation efficiency.

### 4.1 Key Findings

- i. **Reduction in Total Travel Distance:** The optimized routes reduced travel times by 22% on average, enhancing service efficiency.
- ii. **Time Efficiency:** Delivery times dropped by an average of 18%.
- iii. **Cost Savings:** Fuel costs and maintenance expenses were reduced by 20%, validating the model's economic viability.
- iv. **Environmental Impact:** Reduced travel distances led to a 12% decrease in emissions, contributing to environmental sustainability and fuel usage.

### 4.2 Graphical Representation



- i. **Total Distance Traveled (Bar Chart):** Displays total distance pre- and post-optimization, showing significant reduction.
- ii. **Travel Time Savings (Line Graph):** Represents average time taken per route, comparing baseline and optimized routes.
- iii. **Operational Cost Savings (Pie Chart):** Illustrates the proportion of cost savings from fuel and maintenance reduction.
- iv. **Environmental Impact (Line Graph):** Shows emission levels decreasing over time as optimized routes are implemented.

## 5.0 CHALLENGES AND LIMITATIONS

While VRP optimization shows promise, certain challenges remain:

- i. **Data Gaps:** Limited access to real-time traffic data reduced the precision of our model, particularly during peak hours.
- ii. **Infrastructure Constraints:** Sokoto's road conditions necessitated rerouting in certain areas, limiting the potential for optimization.
- iii. **Stakeholder Coordination:** Effective VRP implementation requires collaboration between private and public entities, which is still limited.

## 6.0 RECOMMENDATIONS

To maximize VRP benefits in Sokoto, we recommend:

- i. **Investment in Traffic Data Infrastructure:** Improved data collection through traffic sensors and monitoring systems would enhance model accuracy.
- ii. **Road Infrastructure Upgrades:** Addressing infrastructure deficiencies, particularly in high-traffic areas, would support smoother routing and increased efficiency.
- iii. **Incentives for Sustainable Practices:** Encouraging the adoption of fuel-efficient vehicles and eco-friendly practices among fleet operators could further reduce costs and emissions.

Fig Total Distance Travelled

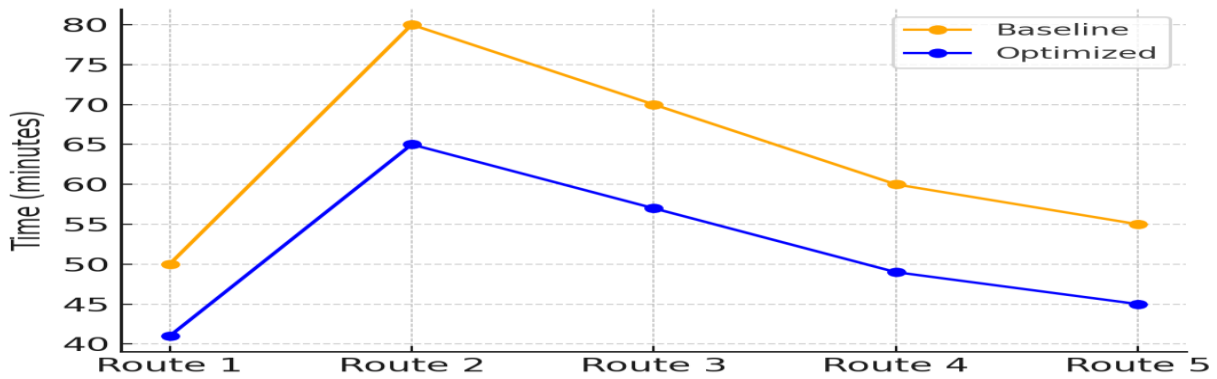


Fig. Travel Time Across Routes

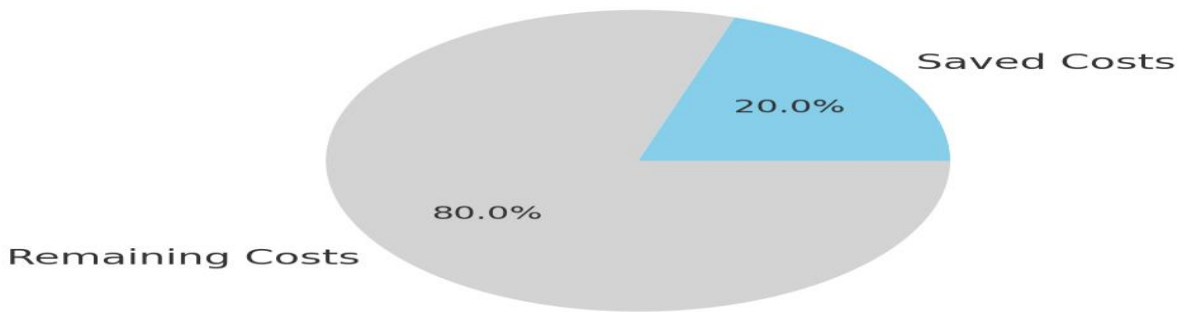


Fig 3. Cost Saving from VRP Optimization

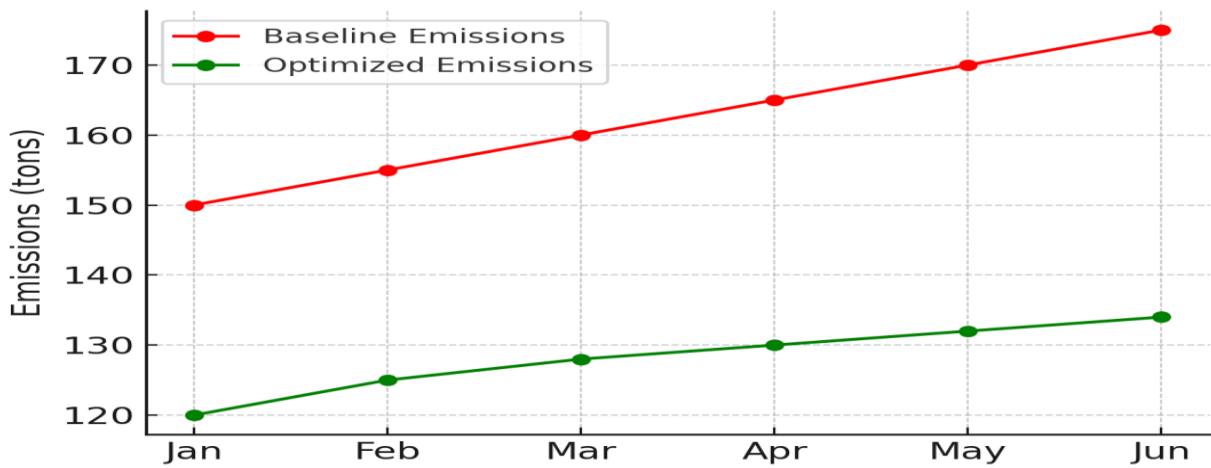


Fig. Emissions Reduction Over Time



