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Geographic Information Systems and MATLAB Simulation to Quantify and Analyze Traffic Congestion in Oja Oba Road, Arakale Road, and FUTA North Gate Road of Akure, Ondo State, Nigeria

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ABSTRACT: Urban traffic congestion presents persistent challenges to transportation efficiency, economic productivity, and environmental health, particularly in rapidly urbanizing cities. Hence, the objective of this paper is to quantify and analyze traffic congestion in Oja Oba Road, Arakale Road, and FUTA North Gate road of Akure, Ondo State, Nigeria using a combination of Geographic Information Systems (GIS) and MATLAB simulation. In this study, data collected include vehicle speed, travel time, GPS tracking, and odometer markings. The Greenshields traffic model, applied within MATLAB, provided insights into speed-density and flow-density relationships. The result shows that Motorcycles are most prevalent on Arakale Road (8618 ± 3045), with extended travel periods (3153 ± 1153). Tricycles are common on Arakale and Oja-Oba, but their activity on North Gate is minimal. Cars exhibit the highest traffic on North Gate (7169 ± 1794) and Oja-Oba (11753 ± 894) while Buses are heavily concentrated on North Gate road (1696 ± 522). Vans and Trucks have limited traffic overall, with North Gate having the highest volumes, highlighting its importance for goods and freight transport. Travel Durations are longest on North Gate Road for all vehicle types, suggesting higher congestion compared to the other routes. Findings revealed peak congestion during evening hours and distinct congestion patterns across road types, with motorcycles and cars as the primary contributors to traffic volume. This GIS-MATLAB integration offers a robust tool for urban planners, allowing detailed congestion analysis and supporting data-driven strategies to enhance traffic management. The framework can be adapted for other urban centers facing similar congestion issues, facilitating more effective transport infrastructure planning.

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Traffic congestion is a pervasive issue in rapidly urbanizing cities worldwide, posing significant challenges to efficient transportation, economic productivity, and environmental sustainability. In Nigeria, urban centers like Akure are increasingly experiencing congestion due to growing populations, rising vehicle ownership, and limited road infrastructure. As cities expand, congestion disrupts daily life, extending commute times, increasing fuel consumption, and exacerbating air pollution. Effective management of traffic congestion has therefore become a priority for urban planners and policymakers, necessitating accurate methods to quantify, analyze, and predict congestion patterns.

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The complexity of urban traffic congestion arises from a variety of factors, including high vehicle density, inadequate road capacity, and fluctuating travel demand. Traditional methods of measuring congestion, such as travel delay and volume-to-capacity ratios, often lack the precision required for dynamic urban environments where traffic patterns shift throughout the day. Emerging technologies like Geographic Information Systems (GIS) and advanced simulation software such as MATLAB provide a solution by enabling the spatial and temporal analysis of traffic patterns. GIS offers powerful tools for mapping traffic data, analyzing spatial relationships, and visualizing congestion hotspots, while MATLAB facilitates detailed simulations of traffic flow and congestion indices. The integration of GIS and MATLAB enables a spatially accurate and predictive approach to congestion analysis, offering insights that are valuable to both researchers and transportation authorities. By identifying peak congestion times and mapping congestion intensity, this study aims to support urban planning efforts in Akure and serve as a model for other cities facing similar challenges. One approach to understanding congestion is by examining demand-capacity relationships (Rothenberg, 1985). Rosenbloom (1978) define congestion as a phenomenon occurring when demand for road use surpasses its capacity, resulting in slower travel times and bottlenecks. Vuchic (1994) attributes congestion to the imbalance between the number of vehicles and road infrastructure capacity. These early definitions provide a foundation for modern studies on congestion dynamics, particularly in urban centers with limited infrastructure. With technological advancements, Geographic Information Systems (GIS) have become invaluable tools for urban traffic analysis and congestion mapping. GIS enables the spatial analysis of traffic flow patterns, vehicle density, and congestion hotspots by integrating traffic data with geographic coordinates. Weisbrod *et al.* (2001) emphasize that GIS-based mapping can visually illustrate areas of high and low congestion, assisting urban planners in targeting high-traffic regions for interventions. By leveraging GIS, transportation planners can analyze congestion in a spatial context, thus identifying temporal and spatial variations that can inform infrastructure improvements and policy measures. This study focuses on developing a novel framework for quantifying traffic congestion in Akure, leveraging GIS and MATLAB to provide a comprehensive analysis of three key roadways: Oja Oba, Arakale Road, and Akure-Ilesha Expressway (FUTA North Gate). The study employs vehicle speed and travel time data to compute congestion levels, applying the Greenshields model to simulate traffic behavior. MATLAB simulation is another vital tool in traffic congestion analysis, particularly in modeling traffic flow and forecasting future congestion patterns. The Greenshields Model, widely applied in MATLAB simulations, assumes a linear relationship between speed and density. Gaus *et al.* (2021) used the Greenshields model to simulate traffic flow, showing that as vehicle density increases, speed decreases—an indicator of congestion buildup. MATLAB's versatility in data processing and visualization makes it suitable for modeling traffic dynamics and predicting congestion trends under different conditions, including peak and off-peak hours. Recent studies have integrated GIS and MATLAB to create comprehensive frameworks for urban congestion analysis. Lomax *et al.* (1997) developed a method to quantify congestion using GIS data and MATLAB simulations, finding that combining spatial analysis with simulation provides more precise insights into traffic conditions. This integration allows for a multifaceted approach to assessing congestion, as researchers can simultaneously visualize spatial congestion patterns and simulate traffic behavior over time. The use of GIS for spatial data and MATLAB for simulation enhances the robustness of congestion studies, particularly in developing cities where data may be limited. Furthermore, traffic congestion studies have highlighted the importance of real-time data for accurate and timely congestion analysis. Weisbrod *et al*. (2001); Lomax and Schrank (2005) suggest that real-time traffic data, such as those gathered from sensors, GPS, and mobile apps, are instrumental for understanding current traffic patterns and for future forecasting. Collecting data on variables like vehicle speed, travel time, and axle spacing allows for detailed congestion metrics that can inform traffic management policies and infrastructure investments. Hence, the objective of this paper is to quantify and analyze traffic congestion in Oja Oba Road, Arakale Road, and FUTA North Gate road of Akure, Ondo State, Nigeria

MATERIAL AND METHODS

Sample Collection: Study area selection criteria included traffic density, road type, and accessibility to capture a representative data set of congestion patterns in the city. Video recorders were mounted at the selected locations to capture traffic data, focusing on three daily time intervals—morning (7-9 am), afternoon (1-3 pm), and evening (4-6 pm). The traffic data was collected for three (3) weeks from Monday to Friday to ensure a robust and comprehensive data set. The continuous recording ensured a comprehensive dataset that could be analyzed for patterns and anomalies. A 100-meter mark was set out to define the exit and entry point for both directions on the road; this was done with an odometer. A handheld Germine GPS was also used to collect spatial information on the road. The recorded videos were processed to count the number of vehicles and analyze traffic flow patterns. Tally sheets were designed for manual counting of vehicles in the recorded videos. Vehicles were categorized as car, bus, truck, van, motorcycle, and tricycle, as tally sheets were designed to count the vehicles. Software tools were used to extract relevant data from the videos, including vehicle types, speeds, and flow rates. Speed and travel time were extracted from the video recordings.

MATLAB Simulation for Traffic Data Collected on the Study Areas: Traffic flow models describe the relationship between traffic density, speed, and volume. In this study, the Greenshields model, which is a common traffic flow model, was adopted. Traffic Flow Models (like Greenshields) help simulate the relationship between speed, density, and flow (Gaus *et al.,* 2021). The Greenshields model assumes a linear relationship between speed (v) and density (k) and is expressed in Eq. (1).

$$v = v_f\left(1 - k/k_j\right) \ldots.(1)$$

Where: v_f is the free-flow speed (maximum speed when there is no traffic); k_j is the jam density (maximum possible density when the traffic is completely stopped).

The traffic flow q is expressed in Eq. (2)

$$q = v \times k \ \ldots.(2)$$

Where q is the traffic flow (veh/h); v is the speed (km/h); k is the density (veh/km).

From the data collected on the field, traffic flow (q) is typically the traffic volume data, which represents the number of vehicles per hour passing through a point.

Given the speed data v and volume data q, then the density, k is calculated using Eq. (3).

$$k = \frac{q}{v} \ldots.(3)$$

Time-series analysis was used to model traffic volume or speed over time. MATLAB has built-in functions for handling time-series data. Speed, density, and flow data were used to compute congestion metrics, providing insights into traffic dynamics across different time intervals and roadways. GIS software was utilized to map the collected data, generating thematic maps that illustrate congestion levels and traffic volumes. Maps were color-coded to represent varying traffic densities and congestion intensity: warmer colors indicated higher congestion, while cooler colors represented lower levels. The processed data was used to develop congestion indices for the three locations, allowing for comparison and visualization of congestion levels over time. Traffic flow and density graphs for each study area were plotted, highlighting the relationship between vehicle density and traffic speed, in line with the Greenshields model. Results were interpreted to identify peak congestion times and areas, providing actionable insights for urban planners.

RESULTS AND DISCUSSION

Traffic Volume: The data collection spanned three weeks to account for accurate traffic variations and determination of regions with peak traffic at varying times of the day. Tables 1 represents traffic volume data collected showing vehicle counts by type (motorcycle, tricycle, car, bus, van, truck) for morning, afternoon, and evening time periods. Table 1 summarizes traffic patterns across Arakale Road, Oja-Oba Road, and North Gate Road, focusing on total vehicle volumes and travel periods for different vehicle types. From the table, it can be observed that Motorcycles dominate traffic on Arakale Road (8618 ± 3045) with significant travel periods (3153 ± 1153), while Oja-Oba and North Gate see much lower volumes. Tricycles are most active on Arakale and Oja-Oba, with negligible presence on North Gate. Cars show the highest traffic on North Gate Road (7169 ± 1794) and Oja-Oba (11753 ± 894), reflecting their use for longer commutes and urban connectivity. Buses are concentrated on North Gate (1696 ± 522), supporting its role as a major public transport route. Vans and Trucks have limited volumes, with North Gate seeing the highest usage for both, suggesting its importance for freight and goods transportation. Travel Periods are generally longest on North Gate Road for all vehicle types, indicating higher congestion levels compared to Arakale and Oja-Oba. The GIS software was used to calculate Average Daily Traffic (ADT) volume for the three (3) selected road sections. The data collected were processed, averaging traffic counts over time during the study. It was therefore used to identify high, medium, and low traffic periods during the day, usually around commuting hours, and calculate average traffic volumes for different time intervals as indicated in Fig. 1. As indicated in Fig. 1, the coloured lines indicate congestion with deep brown for heavy traffic, brown for moderate traffic, and yellow for light traffic displayed by average daily traffic.

Table 1: Total Traffic volume and travel periods for Arakale road, oja-oba road and north gate road for motorcycles, tricycles, car bus and van respectively

	Total Traffic Volume (mean ± std)			**Travel Periods (mean ± std)**		
	Arakale road	Oja-oba road	north gate road	Arakale road	Oja-oba road	North gate road
Motorcycle	8618± 3045	3797 ± 595	1611 ± 702	3153 ± 1153	1536 ± 189	3221 ± 219
Tricycle	1394 ± 691	1184 ± 90	53 ± 9	421 ± 133	544 ± 42	109 ± 4
Car	4645 ±1749	11753 ± 894	7169 ± 1794	1932 ± 832	5582 ± 427	12629 ± 837
Bus	283 ±25	205 ± 31	1696 ± 522	93 ±15	101 ± 21	2871 ± 349
Van	232 ±41	148 ± 32	217 ± 84	93 ±19	70 ± 20	395 ± 49
Truck	139 ±58	122 ± 14	193 ± 35	44 ± 9	49 ± 11	335 ± 27

Std = standard deviation

Greenshields traffic flow model: The greenshields traffic flow model was used to examine the relationship between speed, density, and flow of vehicles on the study roads. The Greenshields Model graphs consist of two plots: one showing the relationship between speed and density, and the other showing the relationship between flow and density. These plots were used to model traffic behavior based on vehicle density on the roads.

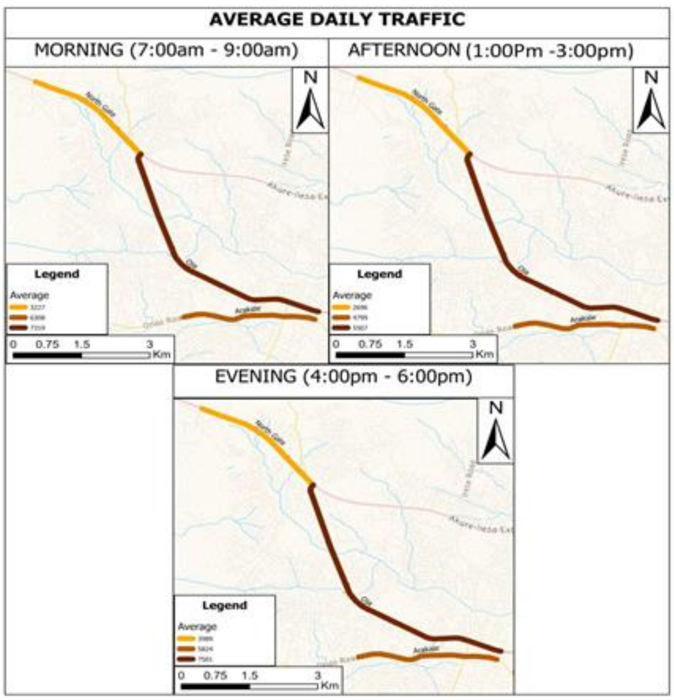

Fig. 1: Average daily traffic volume for the three study areas.

Relationship between speed, density, and flow on Oja Oba road: From Fig. 2, the left graph represents the relationship between speed (in km/h) and density (in vehicles/km) according to the Greenshields model. This model suggests that as vehicle density increases, the average speed decreases linearly. The graph shows a straight, downward-sloping line, indicating that as the density of vehicles on the road approaches a certain threshold, the speed decreases. The left graph aligns with Greenshields' theoretical linear speed-density relationship. On this road, higher vehicle densities lead to lower speeds, which is typical of roads experiencing increasing traffic congestion as density approaches its upper limit. The right graph in Figure 1 represents the relationship between flow (in vehicles/hour) and density (in vehicles/km). According to the Greenshields model, flow initially increases with density up to a certain point, known as "optimal density," where flow reaches its maximum. Beyond this density, flow starts to decrease as congestion builds up. From this graph, the red line pattern in this graph appears erratic, with irregular peaks and drops, suggesting that Oja Oba road experiences fluctuating flow rates as density increases due to congestion and irregular traffic conditions.

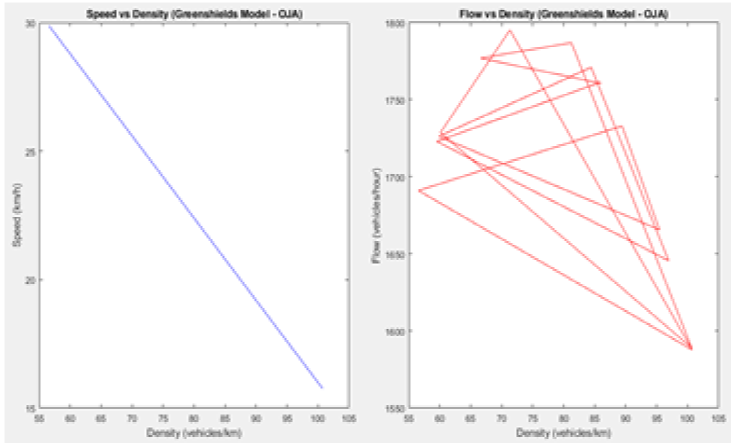

Fig. 2: Greenshields traffic flow model for oja.

Relationship between speed, density, and flow on North Gate road: The left graph in Fig. 3 for the north gate road depicts a linear decline in speed (km/h) as density (vehicles/km) increases, which is consistent with the Greenshields model. At lower densities (around 20-30 vehicles/km), the speed is high (close to 30-32 km/h). This suggests free-flowing conditions with minimal interference from other vehicles. Furthermore, the graph suggests that the northgate road segment can handle a range of traffic densities, with speeds gradually decreasing as density increases. This implies a well-functioning road where congestion builds up gradually and predictably, with no abrupt flow breakdowns. However, as density approaches 70 vehicles/km, the road may start experiencing slower speeds, indicating a near-congested condition as it reaches its effective capacity. The right graph shows a positive correlation between flow (vehicles/hour) and density (vehicles/km) up to around 70 vehicles/km. Flow increases as density rises, suggesting that vehicles are filling the road space effectively and allowing higher traffic flow as density grows. Furthermore, the graph suggests that the northgate road is currently handling traffic well and efficiently using its capacity. However, as density approaches 70 vehicles/km, the road is nearing its maximum flow capacity, suggesting that it could soon face congestion if densities continue to rise. For traffic management, this means the road may need monitoring and potential interventions during peak periods to prevent congestion and ensure smooth traffic flow.

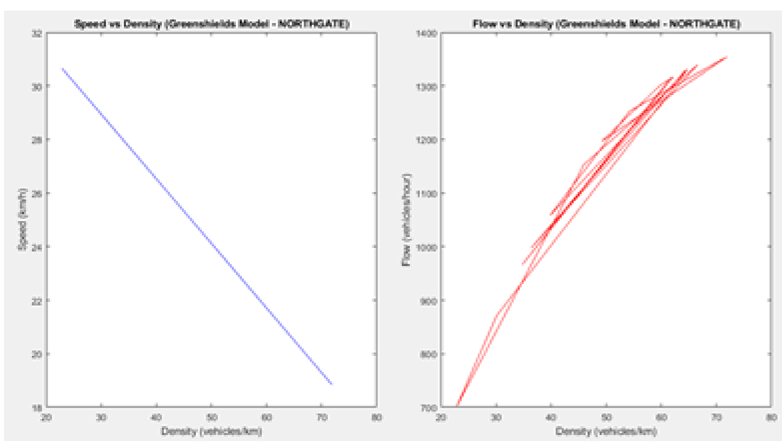

Fig 3: Greenshields traffic flow and density graph for northgate

Relationship between speed, density, and flow on Arakale Road: From Fig. 4, the left graph shows a linear decrease in speed (km/h) as density (vehicles/km) increases, consistent with the Greenshields model. At lower densities (around 40-50 vehicles/km), speed is high (close to 32 km/h), indicating free-flow conditions with minimal interference. As density increases, speed steadily decreases, reaching approximately 18-20 km/h at around 85 vehicles/km. In addition, the graph suggests that the road segment has typical traffic behavior where higher densities lead to slower speeds. It implies that this road can handle increasing traffic density while maintaining a steady decrease in speed, but it may approach congestion as density nears the upper limit (85 vehicles/km). The right graph shows a nonlinear relationship between flow (vehicles/hour) and density (vehicles/km). Flow increases as density rises, reaching a peak flow at around 65-70 vehicles/km. Beyond this density, the road becomes congested, and additional vehicles cause the flow to fluctuate or decrease. This indicates that the road is vulnerable to congestion if densities exceed this critical range, as it cannot sustain high flow beyond this point.

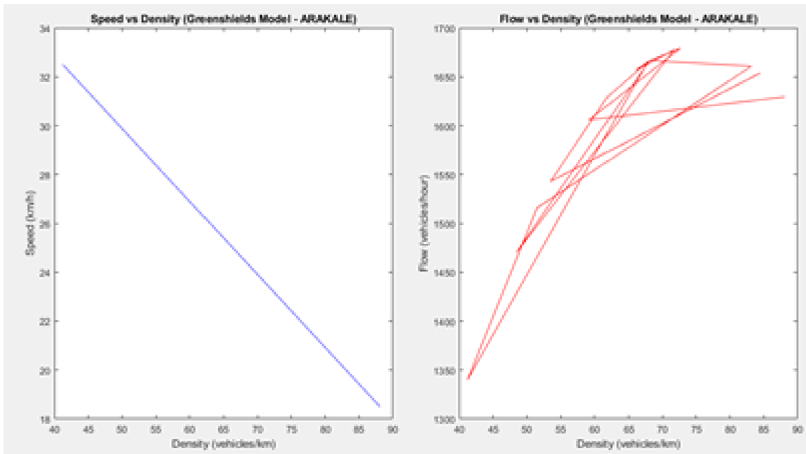

Fig. 4: Greenshields traffic flow and density graph for arakale.

Conclusion: In conclusion, this study presents a GIS-MATLAB integrated framework to analyze urban traffic congestion patterns in Akure, Nigeria. Through detailed data collection on vehicle speeds, densities, and flow rates across three major roads, the analysis identifies congestion during peak hours, with motorcycles and cars as primary contributors. Using the Greenshields model, the study highlights congestion patterns, underscoring the importance of real-time data and regular monitoring for effective traffic management. This framework offers urban planners valuable tools for congestion analysis, supporting data-driven strategies to enhance transportation efficiency and urban infrastructure planning. Future research could expand on this model by incorporating real-time data, examining non-linear traffic models, and exploring policy simulations, all of which would strengthen urban congestion management across rapidly growing cities.

Declaration of Interest: The authors declare no conflict of interest

Data Availability: Data are available upon request from the first author

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