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Statistical Modeling of Space Mean Speed for Accurate Traffic Volume Estimation on Two-Lane Highways in IbadanMetropolis, Nigeria.

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ABSTRACT: This study investigated the statistical modeling of Space MeanSpeed for traffic volume forecasting on two-lane highways in Ibadan metropolis in Nigeria. The focus was on two primary roads: Ojoo–Mokola Expressway and Mokola–Agodi Gates (Queen Elizabeth Road). Statistical Regression analysis model were developed to represent the relationship between space mean speed (u) and traffic density (k). The results obtained revealed correlation coefficient (R) value of 0.9333 and correlation determination (R^2) value of 0.9876 for the Ojoo – Mokola Expressway and correlation coefficient (R) value of 0.8762 and correlation determination (R^2) value of 0.7863 for Mokola – Agodi Gates road; with both road network indicated a positive linear correlation between space mean speed and traffic density. Furthermore, the calibrated space mean speed-traffic density model for both road networks indicated that Ojoo–Mokola road had a better R and R^2 than Mokola–Agodi Gate road. The increase in space mean speed with increasing traffic density during the peak hour was consistent with previous literature. The research provided useful insights for traffic management system and speed control measures, recommending further studies to reduce traffic congestion and improve road safety in Nigeria.

Keywords: Traffic Flow; Speed-Density Model; Highway Traffic; Ibadan Road Networks

I. INTRODUCTION

In Nigeria, highways are the principal means of transportation, playing a significant role in facilitating the socio-economic activities of people (Onokala et al.,2020;). Proper transportation structuring and traffic management system are necessary for the economic advancement and quality of life in urban areas, particularly in developing countries(Anderson, 2016). With progressive growth in traffic levels resulting in traffic congestion, cause by different factors such aswrong parking, slow vehicle speeds, vehicular movement, pedestrian traffic, limited road infrastructure unlawful bus stops, pick–up and drop–off of passenger, vehicle breakdown, narrow road network, religious activities, poor drainage system, increase traffic volume, lack of parking space, lack of traffic lights to coordinate vehicle flow, and driver negligence at some road intersections (Olorunfemi et al., 2014, Ogundare & Ogunbodede, 2014). This hasnecessitated the need for proper traffic flow management in many cities in Nigeria(Adanikin et al., 2023).

Traffic flow refers the interaction among vehicles, drivers, and infrastructure and can either be free-flowing or constrained (Afrin et al.,, 2020). It is a complex phenomenon that is influenced by a variety of factors including: traffic volume, traffic density, traffic speed, road geometry, driver behavior and environmental factors.

Traffic flow has become a great challenge in many cities (He, et al., 2016) such as Ibadan, especially during the peak hours, resulting from an unpredicted growth in number of vehicles which intensifies delay, reduces efficiency on critical roadways and adversely impact the urban region socio-economically (Maji, 2017; Gajjar& Mohandas, 2016).

Addressing these challenges requires dynamic traffic data capture and analysis to inform effective traffic planning, management and infrastructure development. Previous studies have shown that several mathematical traffic volume

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models developed to analyzed congestion cannot be easily generalized or adapted to varying roadway, traffic and control condition. Also they are limited in their inability to adequately capture the complexities of two-lane highways in an urban setting like Ibadan (Irunokhai et al., 2020). Hence, there is a need to develop more adaptable and comprehensive space mean speed- traffic density models that can estimate traffic volumes and help mitigate congestion on Ibadan's two-lane highways (Raji& Muse, 2009).

Accurate traffic volume assessment is a critical aspect of traffic engineering and urban planning, providing the basis for designing road infrastructure, optimizing traffic operations, and ensuring road safety in Two-lane highways(Acheampong, 2020).

Two-lane highways also known as single carriageways, a predominant road network in Ibadan Metropolis, are characterized by bi-directional traffic flow, mixed traffic settings, and limited size.For the highway system to function optimally, an efficient and effective flow of traffic is essential, ensuring operations at designed capacity and favorable levels of service (Salisu et al., 2020).The interactions between vehicles, frequent lane deviations and alternating speeds contribute to traffic congestion and hinder efficient mobility. Therefore, there is a persistent need for an in-depth analysis of the speed-density relationship estimate traffic volume accurately on such highways (Drličiak et al., 2020).

Ibadan, the capital of Oyo State, is a prominent city in southwestern Nigeria. Situated approximately 145 kilometers east of Lagos, it lies between longitude 3°51' East and latitude 7°23' North. Ibadan is well connected to other towns in Nigeria through an extensive network of roads, railways, and air routes (Berry & Horton, 1970). The city comprises 11 local government areas, five of which are urban and six rural. As of the 2006 national census, Ibadan had a population of 2,559,853, with 1,343,147 residing in the urban local governments. This study focuses on two critical road segments in Ibadan: The Ojoo-Mokola road and the Mokola-Agodi Gate road, both of which are under federal jurisdiction. These roads play a vital role in linking major socio-economic hubs, including the Central Business District and the University College Hospital (UCH). Their significant traffic volume under varying flow conditions makes them ideal for studying traffic patterns and formulating speed-density models (Olagunju, 2015).

Conclusively, this study aimed to develop a statistical modeling framework that combines space mean speed and traffic density to achieve accurate traffic volume estimation on two-lane highways in Ibadan Metropolis. By analyzing empirical data collected from key highway segments and incorporating factors such as road geometry, vehicle composition, and driver behavior, the research seeks to establish reliable models for traffic volume prediction.

II. METHODOLOGY

Traffic Survey

Traffic survey was conducted on two selected roads of Ibadan metropolis, Oyo Sate. The roads include: Ojoo – Mokola round about (Old Oyo Road) and Mokola – Agodi (Queen Elizabeth) Dual CW, Mokola bound.These two roads, Ojoo – Mokola round about (Old Oyo Road) and Mokola – Agodi (Queen Elizabeth) road was selected based on the regular traffic congestion experienced on some segements of the road during morning peak period (7:00am and 9:00am) and evening peak period (4:00pm and 6:00pm). The Old Oyo Road has two lanes with the carriage width of 7.3m and existing shoulder width of 1.5m. It originated from Ojoo Market junction and goes through Ibadan Toll Gate and continued its course to Ogun state border. This highway is notorious for skidding away of heavy Lorries and trailers/tankers, also head-on vehicular collision.

Data Collection

Traffic data was collected on the selected roads through videography for morning and evening peak hours for the selected roads between 07:00hrs to 19:00hrs from the 26th of August, 2019 to 6th September, 2019.There are seven traffic composition in consideration; Motorcycle, Tricycle, Cars, Taxi, Buses, Light Truck, Heavy Truck.The hourly traffic count was conducted for five consecutive days after which the summary of the counts was recorded.

Model Formation and Calibration

Using a linear relationship between space mean speed and traffic density, the model equation can be formulated as stated in Equations (1-4) respectively.

Let: $y = a + bx$ (1)

Where: y is the traffic Flow (q), x is the traffic density (k), R is the correlation coefficients, a and b is the constants to be evaluated.

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$$R = \frac{\sum[(x-\dot{x})(y-\bar{y})]}{\sqrt{\sum(x-\dot{x})^2}\times\sqrt{\sum(y-\bar{y})^2}} \quad (2)$$

$$b = \frac{n(\sum xy)-(\sum x)(\sum y)}{n\sum x^2-(\sum x)^2} \quad (3)$$

$$a = \bar{y} + b\dot{x} \quad (4)$$

Where: $\bar{y}$ and $\dot{x}$ are the average values of y and x respectively.

Calculation of Traffic Flow, Spaced Mean Speed and Traffic Density

Traffic Flow (q) is simply defined as the number of vehicles, n, passing some designated highway points in a time interval of duration, t, as expressed by Equation (5) as:

$$q = \frac{n}{t} \quad (5)$$

$$k = \frac{n}{L} \quad (6)$$

$$u = L/A \quad (7)$$

$$A = 1/n \times \sum[1/(L/t)] \quad (8)$$

Where "q" is the traffic flow (veh/hr),
"n" is the number of vehicles,
"t" is the time interval (hr).
"L" is the Length of Highway under study (km),
"t_i" is the time interval of i^{th}vehicle (hr).
"u" is the Space mean speed,
"A" is the travel time taken to travel given length of highway under study
"k" is the traffic density in veh/km

III. RESULTS AND DISCUSSION

This study analyze the speed-density relationship for two major highways in Ibadan, Nigeria: the Ojoo-Mokola Expressway and the Mokola-Agodi Gates (Queen Elizabeth Way). By examining traffic flow, space mean speed, and traffic density data, with aimed to develop accurate models for traffic volume estimation, improving highway traffic management, forecasting and optimization.

Table 1: Summary of Preliminary Traffic Survey

Road Name	Ojoo – Mokola	Mokola – Agodi
Road Conditions:		
Number of Lanes	2	2
Lane width (m)	3.65	3.65
Effective lane width (m)	3.65	3.65
Shoulder width (m)	1.5	1.5
Lateral clearance	1.5	1.5
Design Speed (km/hr)	80	80
Vertical alignment	OK	OK
Horizontal alignment	OK	OK
Control Devices:		
Traffic light	None	None
Traffic Signs	Few	Few
Traffic markings	Few	Few
Traffic regulations	Traffic warden	Traffic warden
Roadside activities		
On- street business	Few	Few
On – street parking	Few	Few

[Ojoo-Mokola Expressway (Old Oyo Road)

Table 2: Traffic Flow, Space Mean Speed, and Traffic Density for Ojoo-Mokola Expressway

Time Interval	Volume, n	1/n	t (hrs)	L (km)	Flow, q = n/t	L/t (km/hr)	1/(L/t)
0700 - 0800HRS	10269	0.0000974	1	1	10269	1	1
0801 - 0900HRS	10248	0.0000976	0.9833	1	10422.05	1.016984	0.9833
0901 - 1000HRS	10425	0.0000959	0.9833	1	10602.05	1.016984	0.9833
1001 - 1100HRS	11122	0.0000899	0.9833	1	11310.89	1.016984	0.9833
1501 - 1600HRS	11991	0.0000834	0.9833	1	12194.65	1.016984	0.9833
1601 - 1700HRS	12311	0.0000812	0.9833	1	12520.09	1.016984	0.9833

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1701 - 1800HRS	12800	0.0000781	0.9833	1	13017.39	1.016984	0.9833
1801 - 1900HRS	10607	0.0000943	0.9833	1	10787.15	1.016984	0.9833
SUM	89773					7.8831	

Table 2, revealed traffic flow, space mean speed and traffic Density for Ojoo-Mokola Expressway.The traffic data for the Ojoo-Mokola Expressway revealed key insights into the space mean speed-traffic density relationship. The computation of regression analysis is depicted in table 3. The constants, for "a" and "b" is evaluated as 1.286 and 58.67respectively; using equation (4), the values of "a" and "b" obtained where used to formulate the model equation:

$$u=1.286k+58.67 \quad (9)$$

The model equation (9) derived suggest that as traffic density (k) increases, the space-mean speed (u) increases, a common phenomenon observed in traffic flow dynamics.

Table 3: Computation of Regression Coefficient for Ojoo-Mokola Road

N	Density(k), x	Speed (u), y	Xy	x - ẍ	y - ȳ	(x - ẍ)(y - ȳ)	(x - ẍ)²	(y - ȳ)²
1	10269	1302.66	13377015.54	-952.63	-120.85	115125.34	907503.9	14604.72
2	10248	1299.996	13322359.01	-973.63	-123.51	120253.04	947955.4	15254.72
3	10425	1322.45	13786541.25	-796.63	-101.06	80507.43	634619.4	10213.12
4	11122	1410.87	15691696.14	-99.63	-12.64	1259.32	9926.137	159.7696
5	11991	1521.10	18239510.1	769.37	97.59	75082.82	591930.2	9523.808
6	12311	1561.70	19226088.70	1089.37	138.19	150540.04	1186727	19096.48
7	12800	1623.73	20783744	1578.37	200.22	316021.24	2491252	40088.05
8	10607	1345.54	14272142.78	-614.63	-77.97	47922.70		
Sum	89773	11388.05	128699097.5			906711.93		
Average (ẍ)	11221.63	1423.51						

Table 4: Computation of Space Mean Speed and Traffic Density for Ojoo-Mokola Road

A	Space Mean Speed, u	Traffic Density
0.000767814	1302.66	10269
0.000769391	1299.996	10248
0.000755989	1322.45	10425
0.000708691	1410.87	11122
0.000657451	1521.10	11991
0.000640108	1561.70	12311
0.00061567	1623.73	12800
0.000743376	1345.54	10607

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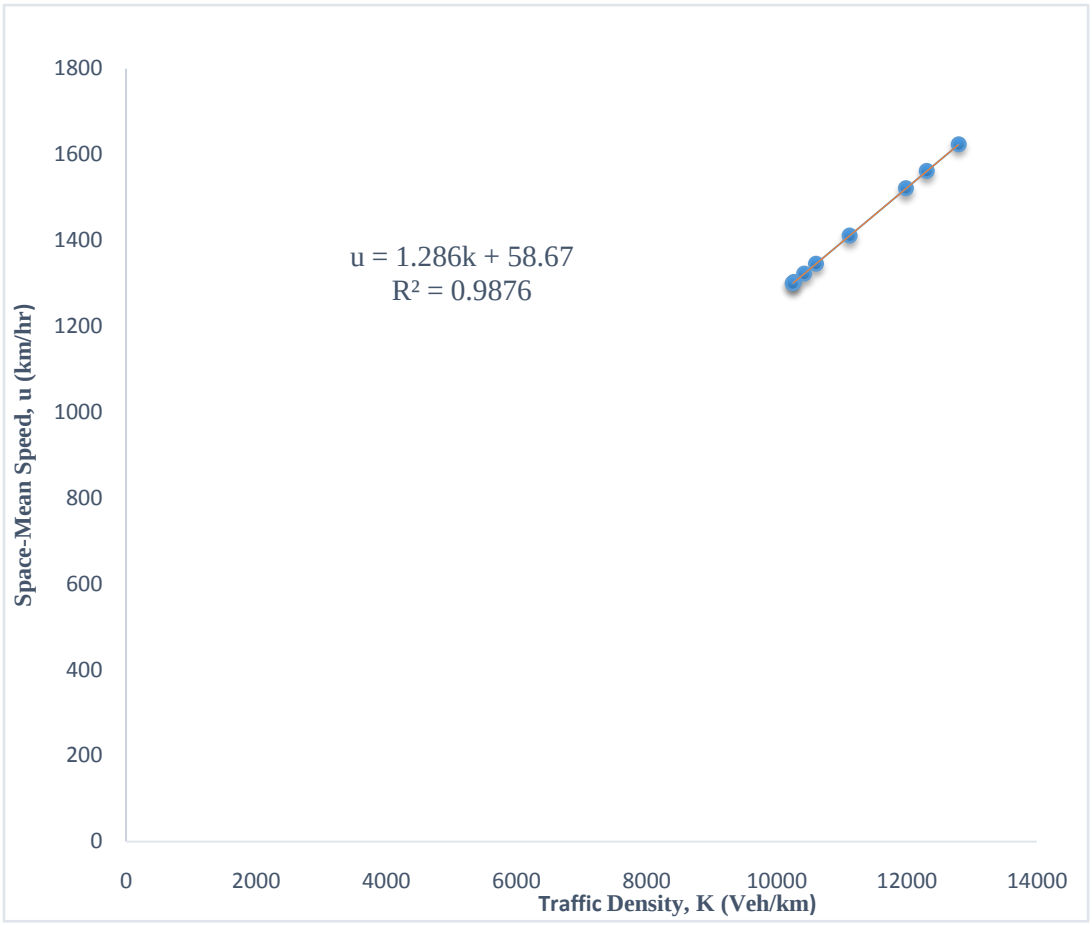

Figure 1: Plot of space mean speed (u) versus Traffic Density (k) for Ojoo- Mokola Expressway

Figure 1; depict a graph of space meanspeed (u) versus traffic density (k) for Ojoo-Mokola Expressway. The graph shows a direct relationship between space mean speed and traffic density. During peak hour, where there are more vehicles along the highway, the traffic density increases thereby creating room for deceleration of vehicles by the drivers to account for maneuveringin congested conditions. This reduction in speed due to increased density is reflective of the bottlenecks caused by merging traffic and other interruptions. Furthermore, when where there are very few vehicles along the highway, the traffic density will reduce and the drivers will be able to travel freely at maximum speed (Uf) of 58.67km/hr, when, traffic density (k) approaches zero (0) which corresponds to the design speed for this road section. Also the correlation determination (R^2)value of 0.9857 from the graph indicate best fit of the data analysis and a strong linear relationship between traffic density and space-mean speed, thus has a very high confidence and less variation of the traffic data.

Mokola-Agodi Gates (Queen Elizabeth Way)

Table 5: Traffic Flow, Space MeaanSpeed, and Traffic Density for Mokola-Agodi Gates

Time Interval	Volume, n	1/n	t (hrs)	L(km)	Flow, q = n/t	L/t (km/hr)	1/(L/t)
0700 - 0800HRS	17415	0.00005742	1	1	17415	1	1
0801 - 0900HRS	15885	0.00006295	0.9833	1	16155	1.016984	0.9833
0901 -	16996	0.00005884	0.9833	1	17285	1.016984	0.9833

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1000HRS							
1001 - 1100HRS	17403	0.00005746	0.9833	1	17697	1.016984	0.9833
1501 - 1600HRS	20701	0.00004831	0.9833	1	21053	1.016984	0.9833
1601 - 1700HRS	16157	0.00006189	0.9833	1	16431	1.016984	0.9833
1701 - 1800HRS	16978	0.0000589	0.9833	1	17266	1.016984	0.9833
1801 - 1900HRS	14468	0.00006912	0.9833	1	14714	1.016984	0.9833
SUM	136003						7.8831

Table 5, revealed traffic flow, space mean speed and traffic density for Mokola-Agodi Gates.The traffic data for the Mokola-Agodi Gates revealed key insights into the space mean speed-traffic density relationship. The computation of regression analysis is depicted in table 6. The constants, for "a" and "b" are evaluated as 0.1268 and 29.76 respectively; using equation (10), the values of "a" and "b" obtained where used to formulate the model equation:

$$u=29.76+0.1268k \quad (10)$$

The model equation (10) derived suggest that as traffic density (k) increases, the space mean speed (u) increases, a common phenomenon observed in traffic flow dynamics.

Table 6: Computation of regression coefficient for Mokola – Agodi Road

N	Density(k), x	Speed (u), y	Xy	x - ẍ	y - ȳ	(x - ẍ)(y - ȳ)	(x - ẍ)²	(y - ȳ)²
1	17415	2209.224	38473635.96	414.625	56.674	23498.46	171913.9	3211.942
2	15885	2015.149	32010641.87	-1115.38	-141.401	157715.85	1244073	19994.24
3	16996	2155.908	36641812.37	-4.375	-0.642	2.81	19.14063	0.412164
4	17403	2207.686	38420359.46	402.625	51.136	20588.63	162106.9	2614.89
5	20701	2625.825	54357203.33	3700.625	469.275	1736610.80	13694625	220219
6	16157	2049.663	33116405.09	-843.375	-106.887	90145.82	711281.4	11424.83
7	16978	2153.712	36565722.34	-22.375	-2.838	63.50	500.6406	8.054244
8	14468	1835.267	26552642.96	-2532.38	-321.283	813610.64	6412948	103222.8
Sum	136003	17252.434	140069966000			2842236.51	22397431.88	360696.17
Average (ẍ)	17000.38	2156.55						

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Table 7: Computation of Space Mean Speed and Traffic Density for Mokola – Agodi Road

A	Space Mean Speed, u	Density
0.000452648	2209.22412	17415
0.000496241	2015.149308	15885
0.000463842	2155.908378	16996
0.000452963	2207.686198	17403
0.000380833	2625.825894	20701
0.000487885	2049.663095	16157
0.000464315	2153.712206	16978
0.00054488	1835.266912	14468

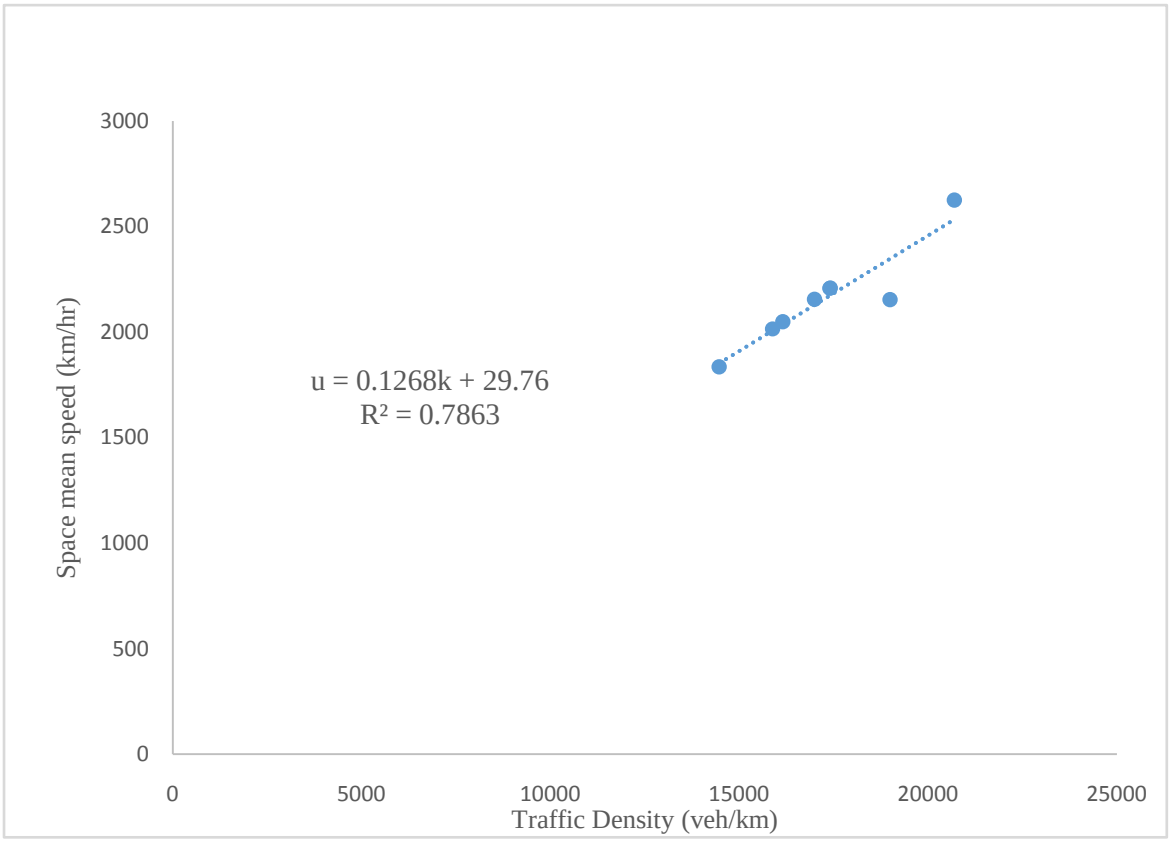

Figure 2: Plot of Traffic Flow (q) versus Traffic Density (k) for Mokola – Agodi Gates (Queen Elizabeth way)

The Figure 2, also a direct relationship between space mean speed and Traffic density for Ojoo- Mokola Expressway. During peak hour, where there are more vehicles along the highway, the traffic density will increase thereby creating room for deceleration of vehicles by the drivers to account for maneuvering. Furthermore, when where there are very few vehicles along the highway during the off peak hour, the traffic density will decrease, and the drivers will be able to travel freely at maximum speed (Uf)of 29.76 km/hr, when, traffic density (k) approaches zero (0) which corresponds to the design speed for this road section. Also the correlation determination (R^2) value of 0.7863 from the graph indicate best fit of the data analysis and a strong linear relationship between traffic density and space-mean speed, thus has a very high confidence and less variation of the traffic data.

Comparison of the Two Highways

A comparison of the two roads highlights important differences in their traffic dynamics. Although both roads have two lanes, the Ojoo-Mokola Expressway exhibits a higher correlation between Space Mean Speed and traffic density,

which can be attributed to its relatively better structural conditions and lower occurrence of accidents or vehicle breakdowns. The free-flow speed on Ojoo-Mokola is also higher, consistent with the expectation for roads that are in better condition and with less heavy vehicle presence.Although in line with study comparison, this study recognizes some limitations, such as the focus on only two major roads in Ibadan, which may not fully represent traffic behavior across all two-lane highways in the region. Future research could expand to include more diverse road types, traffic compositions, and environmental factors to develop more generalized models. Additionally, incorporating real-time data from traffic monitoring systems could provide more accurate and up-to-date traffic forecasts.

Practical Implications

The findings from this study have significant implications for traffic management system and road maintenance in Ibadan metropolis, Nigeria. The developed Space Mean Speed- traffic density models can be used for better traffic volume estimation, improving traffic flow predictions, and enhancing the efficiency of road infrastructure. The model equations derived for both roads: u = 1.286k + 58.67 for Ojoo-Mokola and u = 29.76 + 0.1268k for Mokola-Agodi, provide a basis for optimizing traffic flow and reducing congestion.In practical terms, these models can help predict traffic volume at various times of day, allowing for more effective traffic control measures and road management. For example, the jam density (k□)and free-flow speed (u_x) values can inform road maintenance schedules, suggesting when certain areas of the highway might need repairs or improvements to reduce congestion. Additionally, traffic forecasting models based on these equations can be integrated with intelligent traffic management systems to dynamically adjust signal timings and other control devices. Furthermore, the study also underscores the need for continuous data collection and analysis to refine these models over time. Changes in traffic patterns, infrastructure improvements, or demographic shifts may affect the speed-density relationship, necessitating periodic recalibration of the models.

IV. CONCLUSION

The research indicates that traffic flow, space mean speed, and traffic density on both roads follow predictable patterns, and there is a clear relationship between these factors. The calibrated models help in understanding traffic dynamics, with Ojoo-Mokola Road showing a better fit in its space mean peed-traffic density relationship compared to the Mokola-Agodi Gates Road. These findings are significant for future traffic management and the calibration of speed models in similar road networks.

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