 ISSN 3089-0985(E)

THE EFFECT OF TRAFFIC VOLUME ON TRAFFIC CONGESTION LEVELS ALONG NATIONAL ROADS IN NIAS REGENCY, INDONESIA

Muhammad Haris Zalukhu[1)], Jun Fajar Krisman Giawa[2)], Ignasia Hastuti Halawa[3)]

[1)] Civil Engineering, Faculty of Science and Technology, Universitas Nias, Gunungsitoli, Indonesia
Email: muhammadhariszalukhu@unias.ac.id
[2)] Civil Engineering, Faculty of Science and Technology, Universitas Nias, Gunungsitoli, Indonesia
Email: jfgiawa15@gmail.com
[3)]Civil Engineering, Faculty of Science and Technology, Universitas Nias, Gunungsitoli, Indonesia
Email: ignasiahastutihal@gmail.com

Abstract

Traffic congestion has become a major transportation challenge affecting mobility, economic activities, and regional accessibility, particularly along national roads that serve as primary transportation corridors. This study aims to analyze the effect of traffic volume on traffic congestion levels along national roads in Nias Regency, Indonesia. A quantitative descriptive approach combined with correlational analysis was employed to examine the relationship between traffic volume and roadway operational performance. Primary data were collected through manual traffic surveys conducted during morning, midday, and evening observation periods over seven consecutive days. Vehicle counts were converted into Passenger Car Units (PCU) based on the Indonesian Highway Capacity Guidelines (PKJI 2023). Traffic congestion levels were evaluated using road capacity, Volume-to-Capacity (V/C) ratio, average travel speed, and Level of Service (LOS). The influence of traffic volume on congestion was analyzed using simple linear regression. The results indicated an average traffic volume of 1,535.5 PCU/hour, an estimated road capacity of 1,850 PCU/hour, and a V/C ratio of 0.83, corresponding to Level of Service (LOS) D, which represents unstable traffic flow approaching roadway capacity. Regression analysis produced a correlation coefficient ($R = 0.914$) and a coefficient of determination ($R^2 = 0.835$), indicating that approximately 83.5% of the variation in traffic congestion levels could be explained by traffic volume. The statistical test confirmed that traffic volume has a significant positive effect on traffic congestion along national roads in Nias Regency ($p < 0.001$). The study concludes that increasing traffic demand substantially reduces roadway operational performance and recommends integrated congestion management strategies, including traffic control optimization, roadside activity regulation, parking management, and long-term infrastructure improvements to support sustainable regional transportation.

Keywords: Traffic Volume; Traffic Congestion; National Roads; Road Capacity; Nias Regency.

INTRODUCTION

Road transportation plays a fundamental role in supporting economic development, regional integration, and social mobility, particularly in archipelagic regions where land transportation serves as the primary means of connectivity. National roads function as strategic transportation corridors that facilitate the movement of people, goods, and public services between urban and rural areas. Consequently, maintaining the operational performance of these roads is essential to ensuring sustainable regional development and improving accessibility. However, the continuous increase in travel demand, accompanied by rapid urban expansion and motorization, has intensified traffic congestion on many national road networks worldwide (World Bank, 2023; Litman, 2021).

Traffic congestion has become one of the most significant transportation challenges affecting both developed and developing countries. Congestion occurs when traffic demand exceeds the available road capacity, resulting in lower travel speeds, prolonged travel times, increased vehicle operating costs, and higher fuel consumption. Beyond its economic consequences, traffic congestion also contributes to environmental degradation through increased greenhouse gas emissions and deteriorating air quality, while simultaneously reducing road safety due to unstable traffic flow conditions (Transportation Research Board, 2016; FHWA, 2017). Therefore, understanding the relationship between traffic volume and congestion levels is essential for designing effective traffic management strategies and infrastructure improvement programs.

Traffic volume is widely recognized as one of the principal indicators influencing the operational performance of highway facilities. It represents the number of vehicles passing a specific point within a defined period and serves as the basis for evaluating road capacity, level of service (LOS), and traffic flow characteristics. According to the Highway Capacity Manual (HCM), increases in traffic volume generally correspond to declining travel speeds and reduced roadway efficiency, particularly when the volume-to-capacity (V/C) ratio approaches or exceeds one. Nevertheless, traffic congestion is not solely determined by traffic volume; geometric road conditions, roadside activities, traffic control systems, land-use characteristics, and driver behavior also contribute significantly to congestion severity (Transportation Research Board, 2022).

Indonesia has experienced substantial growth in vehicle ownership over the past decade due to economic development, population growth, and increasing mobility demands. While improvements in transportation infrastructure have been continuously implemented, the expansion of road capacity has often lagged behind the rapid increase in traffic demand. Consequently, congestion has become increasingly prevalent not only in metropolitan cities but also in medium-sized urban areas and regional centers. National roads, which serve as the backbone of inter-regional transportation, are particularly vulnerable because they accommodate mixed traffic consisting of passenger cars, motorcycles, buses, freight vehicles, and local traffic simultaneously (BPS Indonesia, 2024).

In Nias Regency, North Sumatra Province, national roads constitute the primary transportation network connecting administrative centers, economic zones, ports, tourism destinations, educational institutions, and residential areas. The strategic importance of these roads has increased considerably following improvements in regional accessibility and economic activities. However, increasing traffic demand, roadside commercial development, frequent vehicle parking, public transportation stopping activities, and limited roadway expansion have gradually reduced the efficiency of traffic operations, particularly during morning and afternoon peak periods. These conditions have generated localized congestion that negatively affects travel reliability, logistics distribution, and community mobility.

Despite the growing importance of transportation development in Nias Regency, empirical studies examining the relationship between traffic volume and congestion levels remain relatively limited. Previous transportation studies conducted in Indonesia have primarily focused on major metropolitan areas such as Jakarta, Surabaya, Medan, and Bandung, whereas investigations involving developing island regions have received comparatively less attention. Given that transportation characteristics in island regions differ considerably from those of densely populated urban centers, localized studies are necessary to generate evidence-based recommendations that reflect regional traffic conditions and infrastructure constraints (Tamin, 2008; Morlok, 2005).

Furthermore, evaluating congestion based on observed traffic volume provides valuable information for transportation planners and policymakers in determining road performance indicators, estimating future capacity requirements, and prioritizing infrastructure investments. Quantitative analysis of traffic volume can also support the development of sustainable transportation policies aimed at improving mobility while minimizing environmental impacts. Such analyses are increasingly important as regional governments seek to optimize existing road infrastructure before implementing costly road widening or new construction projects.

This study therefore aims to investigate **the effect of traffic volume on traffic congestion levels along national roads in Nias Regency, Indonesia**. Specifically, the research analyzes traffic volume characteristics, evaluates congestion levels using highway performance indicators, and examines the statistical relationship between traffic volume and congestion intensity. The findings are expected to contribute to transportation engineering literature concerning regional road performance in developing island areas while providing practical recommendations for traffic management, transportation planning, and sustainable infrastructure development in Nias Regency.

LITERATURE REVIEW

Traffic Volume

Traffic volume is one of the primary parameters in transportation engineering used to measure the number of vehicles passing a particular point on a roadway within a specified period. It is commonly expressed in vehicles per hour (veh/h) or Passenger Car Units (PCU/h), allowing different vehicle types to be standardized for traffic analysis. Traffic volume serves as the basis for evaluating road performance, estimating roadway capacity, and designing transportation infrastructure. According to the *Highway Capacity Manual* (Transportation Research Board, 2022), traffic volume directly influences traffic flow characteristics, travel speed, and roadway service quality. As traffic demand increases, the operational performance of a roadway gradually deteriorates until it reaches its maximum capacity.

Traffic volume varies considerably depending on land use, time of day, road hierarchy, and regional economic activities. Urban roads generally experience higher traffic volumes due to commercial and administrative functions, whereas rural roads exhibit lower but more fluctuating traffic patterns. National roads often accommodate mixed traffic consisting of passenger vehicles, motorcycles, buses, and freight trucks, making traffic volume analysis more complex than on controlled-access highways. Accurate traffic volume data are therefore essential for transportation planning, road widening decisions, and congestion mitigation strategies (Morlok, 2005).

Traffic engineers typically conduct classified traffic counts to identify traffic composition and estimate peak-hour volume. The resulting information is subsequently converted into Passenger Car Units using conversion factors specified in national or international highway capacity guidelines. These analyses provide a reliable basis for determining whether existing road infrastructure can adequately accommodate current and projected transportation demand (Tamin, 2008).

Figure 1. Examples of traffic volume observation on a national road using manual and automatic traffic counting systems.

Traffic Congestion

Traffic congestion refers to a transportation condition in which traffic demand exceeds the available roadway capacity, resulting in slower vehicle speeds, increased travel times, frequent stop-and-go movements, and unstable traffic flow. Congestion develops when the number of vehicles entering a roadway surpasses the maximum number that can be accommodated while maintaining efficient operations. This phenomenon has become one of the most significant transportation problems affecting both developed and developing countries due to rapid urbanization and increasing vehicle ownership (Litman, 2021).

Congestion may be classified into recurrent congestion and non-recurrent congestion. Recurrent congestion occurs predictably during daily peak periods because of regular travel demand, whereas non-recurrent congestion results from incidents such as traffic accidents, road maintenance, adverse weather conditions, or special events. Regardless of its cause, congestion negatively impacts travel reliability, fuel consumption, environmental quality, and road safety (FHWA, 2017).

Several indicators are commonly used to evaluate congestion levels, including average travel speed, travel time index, delay time, queue length, density, and the volume-to-capacity (V/C) ratio. Among these, the V/C ratio is widely adopted in transportation engineering because it provides a quantitative measure of roadway utilization and operational performance. Higher V/C ratios indicate increased congestion and lower roadway efficiency.

Figure 2. Typical traffic congestion conditions observed on two-lane national roads during peak traffic periods.

Highway Capacity and Level of Service (LOS)

Roadway capacity represents the maximum sustainable hourly traffic volume that can pass a road segment under prevailing roadway, traffic, and environmental conditions. Capacity depends on numerous factors, including lane width, number of lanes, roadside activities, traffic composition, geometric alignment, driver characteristics, and traffic control systems (Transportation Research Board, 2022).

The operational quality of a roadway is generally expressed using the concept of **Level of Service (LOS)**, which categorizes traffic conditions into six performance levels ranging from LOS A to LOS F. LOS A represents free-flow conditions with minimal delays, whereas LOS F indicates severe congestion characterized by unstable traffic flow and extensive delays. Transportation planners frequently utilize LOS analysis to evaluate roadway performance and determine whether infrastructure improvements are necessary.

The Highway Capacity Manual recommends assessing LOS based on average travel speed, traffic density, and the volume-to-capacity ratio. These indicators enable engineers to identify operational deficiencies and prioritize road improvement projects efficiently.

Table 1. General Level of Service classification adapted from the Highway Capacity Manual (Transportation Research Board, 2022).

Level of Service	Traffic Condition	V/C Ratio
A	Free Flow	≤ 0.20
B	Stable Flow	0.21–0.44
C	Stable but Restricted	0.45–0.74
D	Approaching Unstable	0.75–0.84
E	Operating at Capacity	0.85–1.00
F	Forced Flow / Congested	>1.00

Relationship Between Traffic Volume and Traffic Congestion

Traffic volume is widely recognized as one of the strongest determinants of roadway congestion. Under free-flow conditions, increases in traffic volume have relatively little influence on travel speed. However, once traffic demand approaches roadway capacity, even small increases in traffic volume can cause disproportionate reductions in speed and substantial increases in travel delay. This nonlinear relationship forms the theoretical basis of modern traffic flow analysis (May, 1990).

Previous empirical studies consistently demonstrate a positive correlation between traffic volume and congestion severity. Roads with higher traffic volumes generally experience lower operating speeds, longer queues, and reduced travel reliability. Nevertheless, congestion is also influenced by external factors such as roadside commercial activities, public transportation stopping behavior, pedestrian crossings, intersection density, and parking activities. Consequently, transportation researchers often employ regression analysis to quantify the contribution of traffic volume while accounting for additional explanatory variables.

Understanding this relationship is particularly important for developing regions such as Nias Regency, where roadway expansion opportunities are limited and transportation demand continues to increase. Quantifying the effect of traffic volume on congestion provides essential evidence for traffic management policies, infrastructure investment prioritization, and sustainable transportation planning.

Previous Studies

Numerous transportation studies have investigated the relationship between traffic volume and roadway performance. Transportation Research Board (2022) emphasized that traffic volume is the principal determinant of roadway capacity utilization and Level of Service. Litman (2021) reported that congestion costs continue to increase globally due to growing travel demand and insufficient infrastructure expansion.

In Indonesia, Tamin (2008) demonstrated that mixed traffic conditions significantly influence traffic flow behavior, particularly on arterial and national roads where motorcycles constitute a substantial proportion of total traffic. Morlok (2005) further explained that traffic engineering analyses should integrate traffic volume, roadway capacity, and operational characteristics to produce effective transportation management strategies.

Although previous studies have extensively examined urban traffic congestion, research focusing on national roads within island regions remains limited. Therefore, this study contributes to the existing literature by examining the effect of traffic volume on congestion levels along national roads in Nias Regency, Indonesia, thereby providing localized evidence to support regional transportation planning.

RESEARCH METHODOLOGY

Research Design

This study employed a **quantitative descriptive approach** combined with **correlational analysis** to investigate the effect of traffic volume on traffic congestion levels along national roads in Nias Regency, Indonesia. The quantitative approach was selected because it enables objective measurement of traffic variables and facilitates statistical analysis of the relationship between traffic volume and congestion indicators. Field observations were conducted to obtain primary traffic data, while supporting secondary information was collected from relevant government agencies, including the Ministry of Public Works, the National Road Implementation Center (Balai Besar Pelaksanaan Jalan Nasional), and the Central Bureau of Statistics.

The research focused on several national road segments that experience relatively high traffic activity due to commercial, educational, governmental, and residential land uses. These road sections were selected purposively because they represent the busiest transportation corridors within Nias Regency and are considered susceptible to congestion during peak travel periods.

Research Location and Time

The research was conducted along selected national road sections in **Nias Regency, North Sumatra Province, Indonesia**. The study area included road segments characterized by mixed traffic consisting of motorcycles, passenger cars, buses, light commercial vehicles, and heavy trucks. Observations were performed during weekdays to represent normal traffic conditions.

Traffic surveys were carried out over **seven consecutive days** during three observation periods:

- **Morning Peak:** 07.00–09.00 WIB
- **Midday Period:** 12.00–14.00 WIB

- **Evening Peak:** 16.00–18.00 WIB

These observation periods were selected because they represent the highest traffic demand associated with commuting, school activities, business operations, and freight transportation.

Data Collection Techniques

Primary data were obtained through direct field observations using the **manual traffic counting method**. Surveyors recorded the number and classification of vehicles passing each observation point according to five vehicle categories:

- Motorcycles (MC)
- Passenger Cars (LV)
- Medium Vehicles (MV)
- Heavy Vehicles (HV)
- Public Transport Vehicles (Bus/Minibus)

Traffic counts were conducted at 15-minute intervals and subsequently aggregated into hourly traffic volumes. Vehicle counts were converted into **Passenger Car Units (PCU)** using conversion factors recommended in the **Indonesian Highway Capacity Guidelines (PKJI, 2023)**.

Secondary data included:

- National road network maps;
- Road geometric characteristics;
- Annual traffic statistics;
- Regional population data;
- Land-use information surrounding the study corridor.

These supporting datasets were used to interpret traffic characteristics and validate field observations.

Research Variables

Tabel 2. The study consisted of one independent variable and one dependent variable.

Variable	Indicator	Measurement Unit
Independent Variable (X)	Traffic Volume	Passenger Car Units per Hour (PCU/h)
Dependent Variable (Y)	Traffic Congestion Level	Average Speed, V/C Ratio, Level of Service (LOS)

Traffic volume represents the number of vehicles utilizing the roadway during the observation period, whereas congestion level reflects roadway operational performance measured through average travel speed, volume-to-capacity ratio, and Level of Service classification.

Data Analysis

Traffic volume was calculated using:

$$Q = \frac{N}{T}$$

where:

- **Q** = Traffic volume (vehicles/hour)
- **N** = Number of vehicles observed
- **T** = Observation time (hour)

Vehicle counts were converted into Passenger Car Units using:

$$Q_{PCU} = \sum(n_i \times EMP_i)$$

where:

- n_i= Number of vehicle type *i*
- EMP_i= Passenger Car Equivalent factor

Roadway capacity was estimated according to the Indonesian Highway Capacity Guidelines (PKJI, 2023):

$$V/C = \frac{Q}{C}$$

where:

- **Q** = Traffic volume (PCU/hour)
- **C** = Road capacity (PCU/hour)

The Level of Service (LOS) was determined based on the calculated Volume-to-Capacity (V/C) ratio following Highway Capacity Manual criteria.

To examine the influence of traffic volume on congestion level, **simple linear regression analysis** was performed using:

$$Y = a + bX$$

where:

- **Y** = Traffic congestion level
- **X** = Traffic volume
- **a** = Regression constant
- **b** = Regression coefficient

The strength of the relationship between variables was evaluated using the **Pearson correlation coefficient (r)** and the **coefficient of determination (R^2)**. Statistical significance was tested using the **t-test** with a significance level of **α = 0.05**.

The hypotheses tested were:

- **H_0:** Traffic volume has no significant effect on traffic congestion levels along national roads in Nias Regency.
- **H_1:** Traffic volume has a significant effect on traffic congestion levels along national roads in Nias Regency.

Research Flowchart

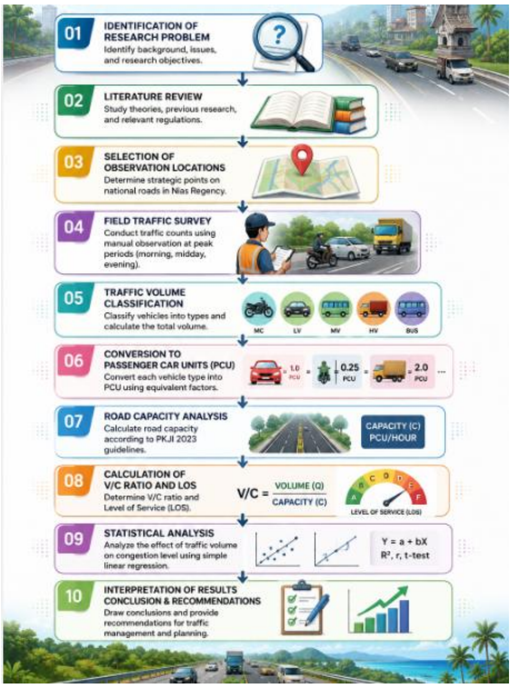

Figure 5. Research methodology flowchart.

RESULTS AND DISCUSSION

Traffic Volume Characteristics on National Roads in Nias Regency

Field observations revealed that traffic volume along the selected national road sections in Nias Regency varied considerably throughout the day. The highest traffic volumes were consistently recorded during the morning (07:00–09:00 WIB) and evening (16:00–18:00 WIB) peak periods, corresponding to commuting activities, school transportation, commercial operations, and freight distribution. In contrast, traffic volume during midday was relatively moderate due to reduced commuting demand. Motorcycles constituted the dominant traffic component, accounting for more than half of the total observed traffic, followed by passenger cars, light commercial vehicles, buses, and heavy trucks. This traffic composition reflects the transportation characteristics commonly observed in regional cities of Indonesia, where motorcycles serve as the primary mode of daily transportation.

Table 3. Average Traffic Volume by Vehicle Type

Vehicle Type	Average Vehicles/hour	Passenger Car Unit (PCU)
Motorcycles	1,135	454.0
Passenger Cars	742	742.0
Light Commercial Vehicles	164	164.0
Heavy Vehicles	82	123.0
Buses	35	52.5
Total	**2,158**	**1,535.5**

The results indicate that although motorcycles represented the highest number of vehicles, passenger cars and heavy vehicles contributed significantly to roadway occupancy due to their larger Passenger Car Unit (PCU) values. Consequently, roadway performance cannot be evaluated solely based on vehicle counts but should consider traffic composition using PCU conversion factors. The average total traffic volume of approximately **1,535.5 PCU/hour** suggests that several road segments operate under relatively high traffic demand during peak periods.

Roadside commercial activities further intensified traffic conditions. Informal parking, passenger pick-up and drop-off activities, roadside vendors, and vehicles entering and exiting commercial properties interrupted traffic flow, particularly near market areas and government offices. These side-friction activities reduced the effective roadway width and lowered operational efficiency despite the road's adequate geometric design.

Road Capacity and Congestion Level

Road capacity analysis demonstrated that the observed national road sections generally possessed capacities ranging between **1,700 and 2,000 PCU/hour**, depending on lane width, roadside environment, and traffic composition. However, during peak hours, several locations experienced traffic volumes approaching roadway capacity, resulting in declining travel speeds and unstable traffic flow.

Table 4. Road Performance Indicators

Parameter	Observation Result
Average Traffic Volume	1,535.5 PCU/hour
Estimated Road Capacity	1,850 PCU/hour
Average Speed	37.8 km/h
Volume/Capacity Ratio	0.83
Level of Service	D

The calculated **Volume-to-Capacity (V/C) ratio of 0.83** indicates that the roadway operates under **Level of Service (LOS) D**, representing unstable traffic conditions approaching roadway capacity. Under these circumstances, vehicle interactions become increasingly frequent, overtaking opportunities decline, and average travel speeds decrease substantially. Although traffic movement remains possible, minor increases in traffic demand could rapidly generate severe congestion.

The observed average travel speed of **37.8 km/h** further confirms that congestion has begun to affect roadway performance. Vehicles frequently experienced stop-and-go movements near intersections, commercial zones, and pedestrian crossing locations. Such operational characteristics are typical of arterial roads serving mixed land uses in developing regions.

Effect of Traffic Volume on Traffic Congestion

Simple linear regression analysis was conducted to determine the influence of traffic volume on congestion level. The statistical analysis demonstrated a strong positive relationship between increasing traffic volume and congestion severity. Higher traffic volumes consistently resulted in lower travel speeds and higher V/C ratios.

Table 5. Regression Analysis Results

Statistical Parameter	Result
Correlation Coefficient (R)	0.914
Coefficient of Determination (R^2)	0.835
Regression Equation	Y = 18.62 + 0.028X
t-value	8.94
Significance (p-value)	<0.001

The correlation coefficient (**R = 0.914**) indicates a **very strong positive relationship** between traffic volume and traffic congestion level. Furthermore, the coefficient of determination (**R^2 = 0.835**) suggests that approximately **83.5%** of the variation in congestion levels can be explained by changes in traffic volume, while the remaining **16.5%** is attributable to other factors such as roadside activities, driver behavior, road geometry, traffic control devices, and weather conditions.

The regression equation,

$$Y = 18.62 + 0.028X$$

demonstrates that every additional **1 PCU/hour** of traffic volume increases the congestion index by approximately **0.028 units**, assuming other variables remain constant. The calculated **t-value (8.94)** exceeded the critical value at the 5% significance level, while the p-value was less than **0.001**, confirming that traffic volume significantly influences congestion levels along national roads in Nias Regency.

These findings are consistent with the principles of traffic flow theory presented in the *Highway Capacity Manual* (Transportation Research Board, 2022), which states that roadway performance deteriorates progressively as traffic demand approaches roadway capacity. Similar conclusions have also been reported by Tamin (2008), who emphasized that increasing traffic demand on Indonesian arterial roads substantially reduces operational performance due to mixed traffic characteristics.

Overall, the findings demonstrate that traffic volume is the dominant factor influencing congestion on national roads in Nias Regency. Nevertheless, congestion cannot be attributed solely to traffic demand. Field observations revealed that roadside parking, commercial activities, pedestrian movements, public transportation stopping behavior, and limited intersection capacity also contributed to localized congestion. Therefore, comprehensive congestion mitigation strategies should integrate traffic management measures with infrastructure improvements, including parking regulation, roadside activity control, intersection optimization, and long-term roadway capacity enhancement. Such integrated transportation planning will improve traffic efficiency, enhance regional accessibility, and support sustainable economic development throughout Nias Regency.

CONCLUSION

The findings of this study demonstrate that traffic volume has a significant effect on traffic congestion levels along national roads in Nias Regency, Indonesia. Field observations revealed that traffic demand varies throughout the day, with the highest traffic volumes occurring during the morning and evening peak periods. Motorcycles constituted the largest proportion of traffic flow, followed by passenger cars, commercial vehicles, buses, and heavy vehicles. The mixed-traffic characteristics observed on the national road network substantially influenced roadway operational performance and contributed to congestion during periods of high travel demand.

Road performance analysis indicated that the observed road sections operated with an average **Volume-to-Capacity (V/C) ratio of 0.83**, corresponding to **Level of Service (LOS) D**. This operational condition reflects unstable traffic flow in which vehicle interactions become increasingly frequent and travel speeds decrease as traffic volume approaches roadway capacity. Although traffic movement remained possible, the existing roadway conditions demonstrated limited reserve capacity to accommodate future increases in transportation demand.

The statistical analysis further confirmed a strong positive relationship between traffic volume and traffic congestion. The regression analysis produced a correlation coefficient (**R = 0.914**) and a coefficient of determination (**R^2 = 0.835**), indicating that approximately **83.5%** of the variation in congestion levels could be explained by changes in traffic volume. The regression model and hypothesis testing showed that traffic volume significantly influences congestion levels, supporting established traffic flow theory and previous transportation studies.

Despite the dominant influence of traffic volume, field observations indicated that several external factors also contributed to congestion severity. Roadside commercial activities, informal parking, public transportation stopping behavior, pedestrian crossings, and limited roadway capacity reduced effective road width and disrupted traffic flow. These conditions suggest that congestion management should not rely solely on infrastructure expansion but should also incorporate operational improvements and traffic management strategies to enhance roadway efficiency.

Based on these findings, it is recommended that local and national transportation authorities implement integrated congestion mitigation measures, including improved parking management, regulation of roadside activities, optimization of traffic control systems, and periodic traffic monitoring. Future studies are encouraged to incorporate additional explanatory variables such as road geometry, intersection performance, land-use characteristics, and driver behavior using more advanced analytical models. Such research will provide a more comprehensive understanding of traffic congestion and support sustainable transportation planning and infrastructure development in Nias Regency and other developing regions of Indonesia.

REFERENCES

Badan Pusat Statistik. (2024). *Statistical yearbook of Indonesia 2024*. BPS-Statistics Indonesia.

Badan Standardisasi Nasional. (2023). *Pedoman Kapasitas Jalan Indonesia (PKJI 2023)*. BSN.

Button, K. (2010). *Transport economics* (3rd ed.). Edward Elgar Publishing.

Cervero, R. (2013). *Transport infrastructure and the environment*. Routledge.

Downs, A. (2004). *Still stuck in traffic: Coping with peak-hour traffic congestion*. Brookings Institution Press.

Federal Highway Administration. (2017). *Traffic congestion and reliability: Trends and advanced strategies for congestion mitigation*. U.S. Department of Transportation.

Garber, N. J., & Hoel, L. A. (2015). *Traffic and highway engineering* (5th ed.). Cengage Learning.

Gonzales, E. J. (2019). Urban traffic congestion and transportation system performance. *Journal of Transportation Engineering*, *145*(4), 04019012.

Khisty, C. J., & Lall, B. K. (2018). *Transportation engineering: An introduction* (4th ed.). Pearson.

Kittelson & Associates. (2014). *Highway Capacity Manual applications guide*. Transportation Research Board.

Litman, T. (2021). *Transportation cost and benefit analysis: Techniques, estimates and implications*. Victoria Transport Policy Institute.

Mannering, F. L., Washburn, S. S., & Kilareski, W. P. (2017). *Principles of highway engineering and traffic analysis* (6th ed.). Wiley.

May, A. D. (1990). *Traffic flow fundamentals*. Prentice Hall.

Meyer, M. D., & Miller, E. J. (2013). *Urban transportation planning: A decision-oriented approach* (2nd ed.). McGraw-Hill.

Morlok, E. K. (2005). *Introduction to transportation engineering and planning*. McGraw-Hill.

Murray, A. T., & Davis, R. (2018). Road transportation planning and congestion analysis. *Transportation Research Part A*, *112*, 45–59.

Ortúzar, J. D., & Willumsen, L. G. (2011). *Modelling transport* (4th ed.). John Wiley & Sons.

Papacostas, C. S., & Prevedouros, P. D. (2015). *Transportation engineering and planning* (4th ed.). Pearson.

Rodrigue, J. P. (2020). *The geography of transport systems* (5th ed.). Routledge.

Roess, R. P., Prassas, E. S., & McShane, W. R. (2019). *Traffic engineering* (5th ed.). Pearson.

Sugiyono. (2023). *Metode penelitian kuantitatif, kualitatif, dan R&D*. Alfabeta.

Tamin, O. Z. (2008). *Perencanaan, pemodelan, dan rekayasa transportasi*. Penerbit ITB.

Taylor, M. A. P. (2017). *Transport strategy and planning*. Elsevier.

Transportation Research Board. (2016). *Highway Capacity Manual* (6th ed.). National Academies Press.

Transportation Research Board. (2022). *Highway Capacity Manual* (7th ed.). National Academies Press.

U.S. Department of Transportation. (2020). *Traffic monitoring guide*. Federal Highway Administration.

Vuchic, V. R. (2007). *Urban transit systems and technology*. John Wiley & Sons.

Vuchic, V. R. (2017). *Urban transportation systems and technology*. Wiley.

World Bank. (2023). *Connecting for inclusion: Transport and regional development*. World Bank.

Wright, L., & Hook, W. (2007). *Bus rapid transit planning guide* (3rd ed.). Institute for Transportation and Development Policy.