JPPIPA 11(4) (2025)

Jurnal Penelitian Pendidikan IPA

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Science Study of Transportation Infrastructure on Energy Consumption and its Impact on Economic Growth in Aceh Province

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Received: January 12, 2025
Revised: March 16, 2025
Accepted: April 25, 2025
Published: April 30, 2025

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DOI: 10.29303/jppipa.v11i4.10897

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Abstract: This study examines the impact of transportation infrastructure on energy consumption and its effect on economic growth in Aceh Province using an infrastructure science approach. Using panel data from 2010 to 2022, the study analyzes the influence of electricity customers per capita, provincial road length in good condition, total road length, real gross fixed capital formation per capita, average years of schooling, government consumption share to real GRDP, and the agricultural sector's GRDP share. The findings reveal that electricity customers per capita, total road length per capita, and average years of schooling have a positive and significant impact on economic growth. In contrast, provincial road length in good condition has a negative and insignificant effect, while real gross fixed capital formation per capita shows a positive but insignificant impact. Meanwhile, government consumption share and the agricultural sector's contribution to GRDP negatively and significantly affect economic growth.

Keywords: Economic growth; Energy consumption; Transportation infrastructure.

Introduction

Economic growth is an important indicator in assessing the development of a region (Wang et al., 2025; Wang & Yang, 2025; Zhao et al., 2024). The increase in the production of goods and services over time reflects an improving economic condition. In this context, transportation infrastructure plays a crucial role in supporting economic activities, especially through the efficient distribution of goods and the mobility of people (Chi, 2024; He et al., 2024; Varghese & Pradhan, 2025). Optimal transportation infrastructure not only increases the efficiency of time and cost in the movement of goods and people but also has a direct impact on scientific aspects such as energy consumption, carbon emissions, and environmental degradation (Azamian, 2025; Dan et al., 2025; Su et al., 2025).

From a scientific perspective, transportation has a close relationship with the disciplines of physics and chemistry, especially in terms of energy consumption and its impact on the environment (Kotiranta et al., 2020; S. Wang et al., 2024; Zhuang et al., 2024). Transportation is one of the main sectors contributing to global energy consumption, mainly from fossil fuels that produce greenhouse gases such as carbon dioxide (CO_2), nitrogen oxides (NOx), and particulate matter (PM) (Mukherjee et al., 2025; Shahveran & Yousefi, 2025; Toumasatos et al., 2024). The application of renewable energy-based technologies, such as electric vehicles and biofuels, is a scientific effort to reduce the carbon footprint and increase energy efficiency in the transportation system. The principles of vehicle aerodynamics, friction between wheels and road surfaces, and energy dissipation in braking systems are also important factors in transportation efficiency and energy consumption (Connolly et al., 2024; Salehin et al., 2025; Zhu et al., 2020).

How to Cite:
Kamal, T. F., & Irfan, M. (2025). Science Study of Transportation Infrastructure on Energy Consumption and its Impact on Economic Growth in Aceh Province. *Jurnal Penelitian Pendidikan IPA*, *11*(4), 1089-1093. https://doi.org/10.29303/jppipa.v11i4.10897

Aceh, as one of the provinces in Indonesia with diverse geographical conditions, faces various challenges in its infrastructure development. Natural disasters such as earthquakes and floods often damage transportation infrastructure, which then impacts the smooth distribution of goods and services. From the perspective of geology and civil engineering, the selection of construction materials with high resistance to natural disasters is very important to maintain infrastructure sustainability. The use of innovative materials such as porous concrete to increase road resistance to waterlogging and geotechnical engineering technology to strengthen bridge foundations in earthquake-prone areas are examples of the application of science in building resilient transportation infrastructure.

In addition, the development of transportation infrastructure must also consider its impact on the surrounding ecosystem (S. Li et al., 2024; Reddiar & Osti, 2022; Sun et al., 2024). From an environmental science perspective, unplanned road and transportation development can lead to habitat fragmentation, increased temperatures due to the urban heat island effect, and air and water pollution from vehicle waste. Therefore, science-based approaches such as environmental impact analysis (EIA), the application of porous road surface technology to reduce rainwater runoff, and the development of green lanes along transportation routes are scientific solutions to reduce negative impacts on the environment (Dias et al., 2025; Y. Li & Feng, 2025; Radzuan & Martin, 2024).

According to the Global Competitiveness Report (2019) by the World Economic Forum, Indonesia still lags behind in terms of infrastructure quality compared to neighboring countries in ASEAN (Mukhamediyev et al., 2023). One of the main obstacles is the uneven infrastructure development, especially in remote areas like Aceh. This can contribute to inefficiencies in energy use in the transportation sector and hinder regional economic growth. Therefore, a science-based approach in the design and implementation of transportation infrastructure is key to improving energy efficiency and supporting sustainable economic growth.

This research aims to analyze the impact of transportation infrastructure on energy consumption and its implications for economic growth in Aceh Province. This study will integrate scientific aspects in energy management, transportation efficiency, and environmental sustainability. With better and science-based transportation infrastructure, it is expected that energy consumption can be reduced, the efficiency of goods and services distribution can be increased, and Aceh's economic growth can develop optimally without neglecting environmental aspects and climate change mitigation.

Method

This research employs a quantitative approach using secondary data obtained from the official publications of the Central Statistics Agency (BPS) as well as various other reliable sources. The data used is panel data covering the period from 2010 to 2022, encompassing 23 districts/cities in Aceh Province. The stages of this research consist of several main steps.

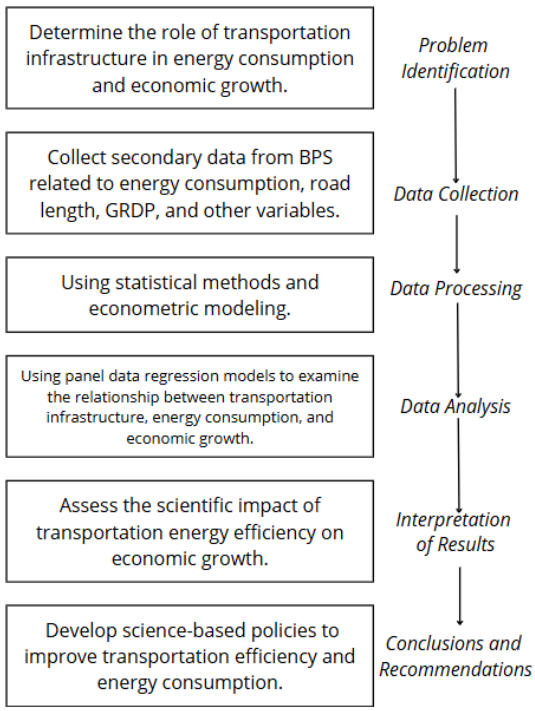

Figure 1. Research Steps

The panel data equation model used in this study is as follows:

$$Y\_1it = \beta\_0 + \beta\_1 〖ELEC〗\_it + \beta\_2 〖GROAD〗\_it + \beta\_3 〖TROAD〗\_it + \beta\_4 〖PMTB〗\_it + \beta\_5 〖AYS〗\_it + \beta\_6 〖CSGRL〗\_it + \beta\_7 〖YAGR〗\_it + \varepsilon\_1i$$

Description:

Y1 = Economic growth

β_0, β = Constant

GRDP = Real Gross Regional Domestic Product per capita

ELEC = Electricity subscribers per capita

GROAD = Total length of road in good condition

TROAD = Total length of road

PMTB = Real gross fixed capital formation per capita

AYS = Average years of schooling

CSGRL = Proportion of government consumption to total real GRDP

YAGR = Proportion of agricultural sector GRDP

ε = Error term

t = Time
i = 23 districts/cities in Aceh Province

The exogenous variables in this study include X_1, X_2, X_3, K_1, K_2, K_3, K_4, while the endogenous variable is Y_1. This model is used to analyze the relationship between transportation infrastructure, energy consumption, and economic growth in Aceh.

Result and Discussion

This study analyzes the impact of transportation infrastructure on energy consumption and its effect on economic growth in Aceh Province using an infrastructure science-based approach. The transportation infrastructure examined includes the provincial road length per capita in good condition (GROAD) and the total road length per capita (TROAD), while energy consumption is analyzed through the number of electricity customers per capita. This study employs an econometric model with a quantitative approach to measure the causal relationship between these variables.

Table 1. Y Equation Estimation Results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	106.2031	1276.259	0.083214	0.9337
LOG(ELEC)	169.7882	152.1958	1.115591	0.2656
LOG(GROAD)	7.451094	20.01940	0.372194	0.7100
LOG(TROAD)	50.69658	33.90435	1.495283	0.1360
LOG(PMTB)	51.71178	60.37795	0.856468	0.3925
LOG(AYS)	891.3029	313.4472	2.843550	0.0048
CSGRL	-0. 418745	0.031936	-13.11209	0.0000
YAGR	-15.74092	7.081042	-2.222966	0.0271
Effects Specification				
R-squared	0.945364		Mean dependent var	2266.178
Adjusted R-squared	0.939452		S.D. dependent var	889.8099
S.E. Of regression	218.9510		Akaike info criterion	13.71081
Sum Squared resid	12847792		Schwarz criterion	14.08300
Log likelihood	-2012.910		Hannan-Quinn criterion	13.85979
F-Statistic	159.9036		Durbin-Watson stat	0.239085
Prob(F- Statistic)	0.000000			

The Impact of Transportation Infrastructure on Economic Growth

The regression estimation results indicate that the provincial road length per capita in good condition (GROAD) has a negative effect on economic growth (GRDP) with a regression coefficient of -7.541. This means that a 1% increase in the provincial road length per capita leads to a 7.541% decline in economic growth. This could be due to road infrastructure investments that have not yet directly boosted economic productivity but are still in the construction phase, which has not yielded an optimal impact on economic growth. Additionally, the distribution and quality of road infrastructure may also affect mobility efficiency.

On the other hand, the total road length per capita (TROAD) shows a positive impact on economic growth, with a regression coefficient of 50.69. This indicates that a 1% increase in the total road length per capita contributes to a 50.69% rise in economic growth. This result supports transportation theory, which states that better connectivity enhances access to resources, accelerates the distribution of goods and services, and expands the labor market.

The Impact of Energy Consumption on Economic Growth

The number of electricity customers per capita has a positive but insignificant effect on economic growth. This finding is consistent with previous studies, which indicate that electricity consumption is closely related to economic activity. The industrial and service sectors account for the majority of electricity consumption, demonstrating that increased energy access can improve production efficiency and people's quality of life. However, inefficiencies in electricity distribution and dependence on unsustainable energy sources may hinder the maximization of its impact on economic growth.

Other Supporting Variables

In addition to transportation infrastructure and energy consumption, other factors influencing economic growth in Aceh include:

Gross Fixed Capital Formation (GFCF) – Has a positive impact with a regression coefficient of 51.71, meaning that increased fixed capital investment contributes to economic growth. This supports the

theory that investments in fixed capital, such as machinery and production equipment, contribute to increased economic output.

Average Years of Schooling (AYS) – Has a positive and significant effect with a coefficient of 891.3, indicating that improving human resource quality through education significantly contributes to economic growth. Better education enhances workforce skills and productivity.

Government Consumption on Real GDP – Has a negative impact of -0.418, indicating that inefficient or uneven government spending can hinder economic growth. This could occur if budget allocations are more focused on consumptive expenditures rather than productive investments.

Agriculture Sector Contribution to GDP – Has a negative effect with a coefficient of -15.74, suggesting that dependence on a less productive agricultural sector can hamper economic growth. This aligns with structuralism theory, which states that economic transition from agriculture to industry and services promotes economic growth.

Coefficient of Determination (R^2)

The R-Square value of 0.945 or 94.53% indicates that this model explains most of the variation in Aceh's economic growth. This means that transportation infrastructure, energy consumption, and other supporting variables play a significant role in determining economic growth in the region, while the remaining 5.47% is influenced by factors outside this model. The model demonstrates high validity in predicting the impact of infrastructure on economic growth.

Conclusion

This study shows that energy consumption has a positive effect on economic growth in Aceh, while transportation infrastructure has a mixed impact: total road length per capita boosts economic growth, but the length of provincial roads in good condition has not had an optimal impact. Other factors such as investment and education contribute positively, while government consumption and the agricultural sector tend to hinder growth. Therefore, it is recommended that the government develop infrastructure in an integrated manner, equalize development policies, and increase support for the agricultural sector for sustainable economic growth.

Acknowledgments
Thank you to all parties who have helped in this research so that this article can be published.

Author Contributions
All authors contributed to writing this article.

Funding
No external funding

Conflicts of Interest
No conflict interest.

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