ISSN: 2599-1086 | e-ISSN: 2656-1778 | Vol. 7 | No. 1

Regional Economic Agglomeration and Trans-Sumatra Toll Road Development: A Network and Spatial Review

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ABSTRACT

Road and transportation networks play a crucial role in interregional connections. One of the key development programs initiated during President Jokowi's presidency in Indonesia is aimed at improving interregional connectivity. In Sumatra, the National Strategic Project *(Program Strategis Nasional/PSN)* for the construction of the Trans-Sumatra Toll Road has been underway since 2014. After a decade of development, it is essential to evaluate the impact of this infrastructure on the region's agglomeration to inform future development policies. This paper reviews the changes in network structures and economic activities as influenced by the construction of the Trans-Sumatra Toll Roads. It also seeks to predict the future development of agglomeration and economic activities. The study employs regional and city planning methodologies, including space syntax, fractal dimension analysis, and cluster analysis. The findings indicate that the construction of the Trans-Sumatra Toll Road has significantly enhanced connectivity and accessibility, increased the gravitational value of the territory, and reduced the load on existing roads. Moreover, the development of toll roads has led to the growth of new economic centers, which eventually resulted in the formation of four major agglomeration regions.

Keywords: Economic agglomeration; Policy evaluation; Road network; Space Syntax

ABSTRAK

Jaringan jalan dan transportasi memiliki peran penting dalam pengembangan koneksi antarwilayah. Salah satu program pembangunan yang dilakukan selama masa kepresidenan Jokowi di Indonesia adalah peningkatan konektivitas antarwilayah. Di Sumatra, pembangunan Proyek Strategis Nasional (PSN) Jalan Tol Trans-Sumatra telah berlangsung sejak 2014. Setelah melewati 10 tahun target pembangunannya, evaluasi perlu dilakukan untuk mengukur sejauh mana pembangunan ini berdampak pada aglomerasi wilayah sehingga hasilnya dapat menjadi dasar kebijakan untuk rencana pembangunan masa depan. Artikel ini bertujuan untuk mengkaji perubahan dalam struktur jaringan dan aktivitas ekonomi yang disebabkan oleh pembangunan Jalan Tol Trans-Sumatra. Artikel ini juga hendak memprediksi perkembangan aglomerasi dan aktivitas ekonomi di masa depan. Cabang keilmuan perencanaan kota dan wilayah digunakan sebagai dasar untuk metode penghitungan, termasuk sintaks ruang, dimensi fraktal, dan analisis klaster. Temuan penelitian menunjukkan bahwa pembangunan Jalan Tol Trans-Sumatra mampu meningkatkan nilai konektivitas dan aksesibilitas secara signifikan, meningkatkan nilai gravitasi wilayah, dan mengurangi beban pada jalan eksisting Pembangunan jalan tol juga memantik pertumbuhan pusat-pusat aktivitas baru, yang pada akhirnya membentuk empat wilayah aglomerasi utama.

Kata Kunci: Aglomerasi ekonomi; Evaluasi kebijakan; Jaringan jalan; Sintaks ruang

ARTICLE HISTORY

Received: April 20, 2024

Revised: June 14, 2024

Published: June 30, 2024

CITATION (APA 7TH)

Hariyanto, A. D., Graha, D. T. R., & Afrianto, F. (2024). Regional economic agglomeration and trans-Sumatra toll road development: A network and spatial review. *Journal of Infrastructure Policy and Management, 7*(1), 75–95.

INTRODUCTION

Under President Joko Widodo's leadership, Indonesia has prioritized on infrastructure development, allocating around IDR 3,309 trillion to various projects over eight years. A notable shift in strategy has expanded the focus from primarily Java-centric projects to a broader geographic regions, including Sumatra. Among these initiatives, the Trans-Sumatra Toll Road stands out, prominently featured in the 2020-2024 National Medium-Term Development Plan (RPJMN) and Presidential Regulation Number 109 of 2020 as a major project (Peraturan Presiden Republik Indonesia Nomor 18 Tahun 2020 Tentang Rencana Pembangunan Jangka Menengah Nasional 2020-2024, 2020).

Although the Trans-Sumatra Toll Road is planned to extend 2,800 km, only 547 km had been completed as of 2023. This includes critical segments connecting major urban and industrial centers across the island (Kementerian Pekerjaan Umum dan Perumahan Rakyat, 2016). The ongoing construction aims to significantly reduce travel times—from 48 to 30 hours between Lampung and Aceh—and to spur the development of industrial and tourism sectors. This infrastructure is crucial for enhancing connectivity between the eastern and western corridors of the island, promising profound economic impacts on the region (Berechman, 1994; Cervero, 2009; Closs & Bolumole, 2015; Hou, 2022).

The Indonesian government's commitment to expanding the toll road network reflects a broader strategy to enhance national connectivity and foster economic growth. Research supports the role of transportation infrastructure in promoting urbanization and economic agglomeration, with positive effects on economic activity and integration within and between urban areas (Berechman, 1994; Chatman & Noland, 2011; Vickerman, 2018; Wei et al., 2022; Ye et al., 2018). Infrastructure not only supports local economies but also facilitates broader regional economic systems, emphasizing the importance of interconnected economic activities and linkages between diverse urban and regional areas across Indonesia (Tao et al., 2020; Wang et al., 2022).

Numerous studies globally have explored the externalities arising from network development on economic agglomeration, yet many overlook the impact of such networks on shifting economic centers and regional growth (Ren et al., 2022). Specific to the Trans-Sumatra Toll Road, while the potential benefits and risks have been extensively discussed, there remains a significant gap in quantitative research assessing its direct impacts on accessibility, connectivity, economic agglomeration, and regional economic growth. This study aims to bridge this gap by integrating three main bodies of literature—transportation infrastructure networks, economic agglomeration, and economic growth—within the framework of regional and urban planning.

The research utilizes the Spatial Design Network Analysis (SDNA) approach, employing algorithms such as Degree of Centrality, Closeness, Network Gravity, and Betweenness Centrality to examine changes in connectivity, accessibility, and transportation infrastructure load across Sumatra (Cooper & Chiaradia, 2020; He et al., 2019). It also incorporates a fractal dimension approach to quantify the level and spatial patterns of economic agglomeration prompted by the construction of the Trans-Sumatra Toll Road, specifically looking at how street intersections contribute to economic clustering (Afrianto, 2023; Kalpana et al., 2021; Shen, 2002). Furthermore, future economic activity centers are projected using night satellite imagery to simulate changes in economic dynamics. These methodologies not only provide a detailed understanding of the economic impacts of the Trans-Sumatra Toll Road but also contribute innovative approaches to regional planning, utilizing big data to enhance the precision of economic and developmental forecasts in Sumatra.

THEORETICAL FRAMEWORK

Connectivity and Accessibility

Networks, as spatial organizational systems, interlink cities and regions through economic and social bonds, generating externalities by integrating and synergizing connected nodes across two key dimensions: the material, which includes tangible infrastructure such as roads, railways, and communication systems, and the non-material, encompassing intangible flows and spatial relationships such as political cooperation and innovation among cities (Tao et al., 2020).

The essence of these networks lies in their connectivity, characterized by interconnected nodes—individuals, companies, cities, and states—that reflect the strength of their relational bonds (Jiao et al., 2020; The World Bank, 2019). Accessibility, on the other hand, relates to the opportunities for individuals to engage in various activities within these networks (Somenahalli et al., 2016). The development of transportation infrastructure plays a crucial role in enhancing both connectivity and accessibility. It profoundly impacts sustainable land use patterns by driving urban expansion, influencing city growth, and affecting land and property prices, thereby significantly reshaping urban and regional landscapes (Song et al., 2012; Sahu & Verma, 2022).

Economic Impacts and Economic Agglomeration Effects of Enhanced Connectivity, Accessibility, and Activity Systems

The development of transportation infrastructure introduces externalities that influence spatial dynamics across cities and regions, potentially driving economic growth at national, regional, and municipal levels (Tao et al., 2020; Weisbrod & Alstadt, 2007; Sahu & Verma, 2022; Tan et al., 2022; Verma et al., 2013; Xie et al., 2017). Such advancements facilitate economic expansion by reducing travel time, lowering travel costs, enhancing the mobility of production factors, and improving overall accessibility and connectivity (Chen & Haynes, 2017; Jiao et al., 2014; Olsson, 2009; The World Bank, 2019). The resultant economic impacts manifest as both immediate and long-term effects at the macro level (Chakrabarti, 2018; Chen & Haynes, 2017; Jia et al., 2017).

As illustrated in Figure 1, these effects can be categorized into direct and indirect impacts. Direct impacts include observable benefits such as travel time and cost savings, environmental improvements, reduced accidents, and job creation from new projects. Indirect impacts, however, emerge from the cascading effects of these direct benefits and encompass increased economic concentration and specialization (Sahu & Verma, 2022). Economic agglomeration, as described by Graham, results from the spatial concentration of economic activities, with its scale influenced by enhanced accessibility and connectivity brought about by infrastructure development (Graham, 2008). Thus, this infrastructure development not only directly affects economic metrics but also induces broader spatial and connectivity-based impacts that shape regional economic landscapes.

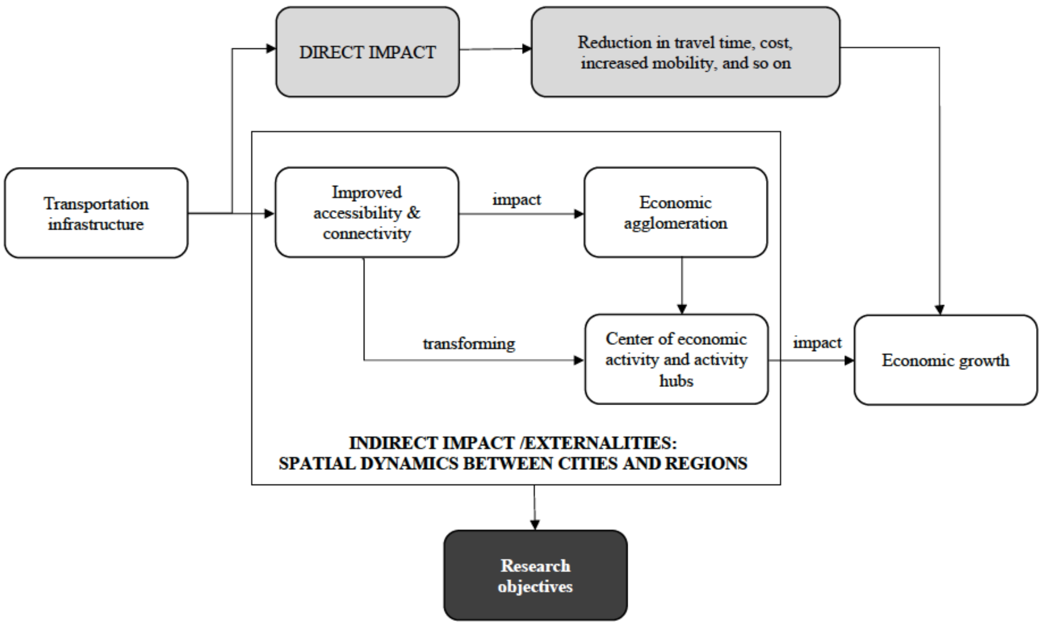

Figure 1. Conceptual frameworks

METHODOLOGY

Research Design

Economic transformation involves significant changes to the economic structure and direction, with the goals of sustainable growth and societal welfare enhancement. Central to this transformation is governmental policy, which is a focal point of research analyzing the National Strategic Project (PSN) of the Trans-Sumatra Toll Road Network development. Initiated in 2015, the PSN has reshaped Sumatra's spatial layout, with an aim for completion in 2024. This study evaluates three temporal states of Sumatra's road network: the pre-PSN in 2013, the current state in 2022 reflecting PSN progress, and the projected state post-completion in 2024. It assesses connectivity, potential agglomeration, and future economic activities.

Spatial Design Network Analysis, based on Space Syntax, is used to evaluate regional connectivity and accessibility. The Cluster analysis, with Density-Based Spatial Clustering of Applications with Noise (DBSCAN) and Fractal Dimension analysis for road intersection distances, assesses the PSN's impact on economic clustering. The study also employs correlation analysis between Tight-Time Light (NTL) satellite imagery and Gross Regional Domestic Product (GRDP) to estimate economic activity. A high correlation suggests that NTL can serve as a proxy for GRDP to predict economic outcomes in 2024 upon the PSN's full realization, as detailed in Figure 2.

The entire analysis process was conducted using several software tools, including Microsoft Excel for correlation analysis, Quantum Geographic Information System (QGIS) for data preparation, the SDNA plug-in for SDNA analysis, the DBSCAN Toolbox for clustering analysis, and Fractalyze 3.0 for generating fractal dimension measurements.

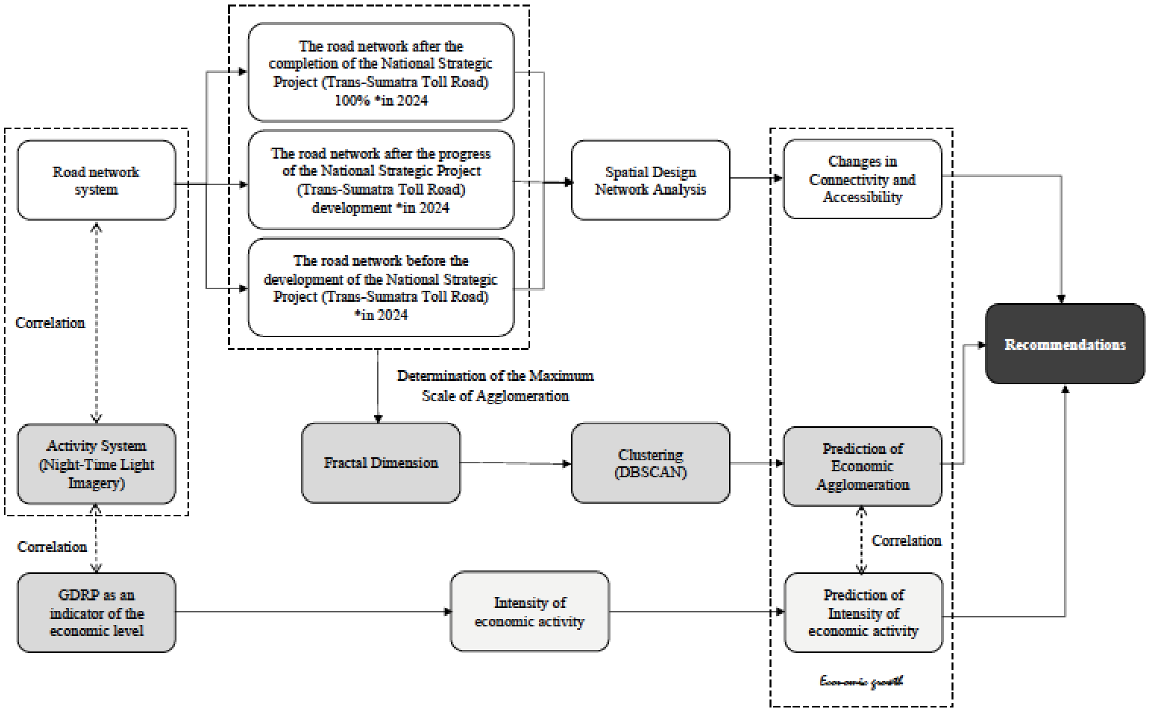

Figure 2. Research frameworks

Data and Data Source

This study involves three analytical concepts that necessitate fairly complex data. The fundamental data required includes information on administrative boundaries. Since network analysis requires data in the form of continuous and uninterrupted networks, the administrative boundaries of Sumatra Island in the mainland area are utilized. Furthermore, to conduct analyses related to accessibility, connectivity, and agglomeration, data on road networks at three different time points are necessary. Additionally, to analyze the intensity of economic activities, Night-Time Satellite imagery and GRDP data for each province in Sumatra are required. Detailed information regarding the research data is elaborated further in the subsequent sections (see Table 1).

Table 1. Research data

No	Type	Sources	Data Acquisition
1	Administrative boundary	Indonesian base map (Indonesian Geospatial Information Agency portal)	August 2023
2	The road network condition before the PSN in 2013	OpenStreetMap data, downloaded from the historical data of Geofabrik	Access Time: August 13, 2023, 9:10 am
3	The road network condition in 2022	Open StreetMap data, downloaded by Plugin QuickOSM QGIS	Access Time: August 13, 2023, 12:00 am
4	The plan for the National Strategic Project (PSN) of the Trans-Sumatra Toll Road	National Mid-Term Development Plan 2020-2024	
5	Projection of the completion of the Trans-Sumatra Toll Road PSN road network (by the end of year 2024)	Data number 3 is processed by incorporating the plan for the Trans-Sumatra Toll Road PSN	Data processed
6	Gross Regional Domestic Product (GRDP)	Central Bureau of Statistics (in each province)	August 2023
7	Night-Time Light (NTL) satellite image	Figshare dataset Harmonization of DMSP and VIIRS Night-Time Light data	Access Time: August 9, 2023, 12:00 am

Source: Researcher (2023)

This study examines the condition of the road network prior to the implementation of the National Strategic Plan (PSN) for the Trans-Sumatra Toll Road, using 2013 as the benchmark year. This initiative, which is a critical component of the 2020-2024 National Mid-Term Development Plan, began construction in 2015 with the goal of expanding the toll road network by an additional 2,031 kilometers by 2024. For a thorough comparative analysis, historical data from 2013 serves as the baseline. To ensure comprehensive analysis, all road network data in shapefile (*.shp) format is meticulously processed to fit the analytical framework. The SDNA and DBSCAN cluster analysis are conducted using the QGIS mapping tool. Meanwhile, the fractal dimension is calculated using Fractalyse, a Java-based software, to elucidate complex patterns of road network growth and its implications for regional development and economic agglomeration. This rigorous methodological approach allows for a detailed assessment of the PSN's impact on the Trans-Sumatra Toll Road, providing insights into the transformative effects of this large-scale infrastructure project.

Analysis Techniques

This research employs three core analytical methods: SDNA, Fractal Dimension Analysis, and Cluster Analysis. SDNA, a graph theory-based spatial configuration analysis, extends beyond the quantitative measures of space syntax, facilitating large-scale network analysis with more robust and accessible data (Cooper & Chiaradia, 2020; He et al., 2019). It is pivotal for assessing the road networks of Sumatra Island, employing algorithms such as Degree of Centrality to indicate network reach, Closeness and Gravity to locate central nodes based on shortest path accessibility, and Betweenness Centrality to highlight frequently chosen routes. These metrics help establish the economic potential of an area through its connectivity and accessibility (Yamu et al., 2021).

Fractal Dimension analysis draws on the concept that natural and urban forms, despite their apparent irregularity, maintain consistent patterns across scales. This concept, aided by GIS technologies and digital mapping, allows the study of urban agglomeration by identifying fractal patterns within city structures. Fractalyse-3.0, utilizing the Box Counting method, helps to analyze the merging processes of growth poles in cities or regions, which is then used to determine the distances for the subsequent DBSCAN cluster analysis.

DBSCAN, a density-based clustering technique, excels in identifying clusters by expanding from high-density core points and integrating neighbouring points, setting apart noise from significant data points (Suthar et al., 2013). This method requires the specification of an epsilon value to define the distance parameter for modeling density. By applying DBSCAN with the distances derived from fractal dimension numbers, this study delineates areas of economic agglomeration. This approach enables a multi-faceted analysis of changes in spatial structures and their economic implications over different phases of road network development in Sumatra.

RESULTS

This section elaborates on the research findings, commencing with the presentation of data on the development of road networks and intersections. The relationships between the studied elements are examined, followed by network and agglomeration analysis, and concluded with forward predictions.

Development of the Road and Intersection Network

As a foundation for analysis and discussion, data is presented on the condition of road network development and intersections. The data includes road length, average length of road sections, and the number of road segments. For intersections, the presented data encompasses the number of intersections and the average branching of roads at each intersection point.

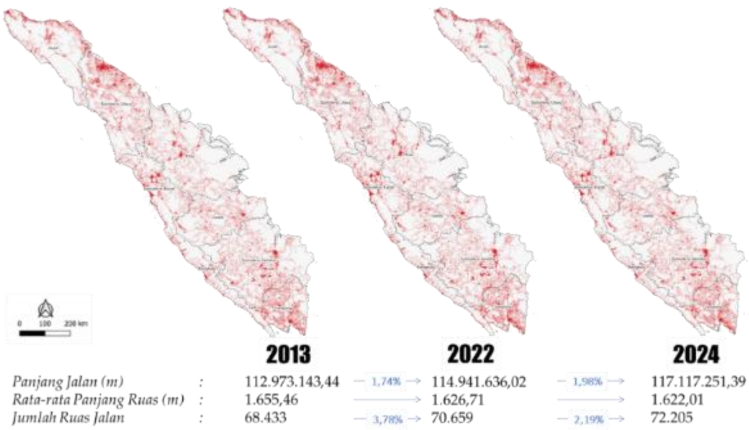

Figure 3. Road network data

Figure 3 shows the findings derived from the network data. The data for the year 2013 reveals a total of 68,433 road segments spanning 112,973 km, with an average length of 1,655.46 meters. By 2022, Sumatra had a total of 70,659 road segments with a total length of 114,941 km and an average length of 1,626.71 meters per road segment. This data differential shows an increment of 2,226 segments and an additional road length of 1,968 km between 2013 and 2022. According to the data processing outcomes, in 2024 after the completion of the PSN road construction, Sumatra's road network will span 117,117 km with a total of 72,205 road segments. Comparing the existing 2022 network to the projected 2024 scenario upon PSN completion indicates a 1.98% increase in road length and a 2.19% increase in the number of road segments.

The road network entails extraction at each road intersection to depict them as aggregation nodes, with the roads forming links connecting these nodes. As per the data processing results shown in Figure 4, the number of intersections (nodes) in Sumatra was 41,873 units in 2013, which increased to 43,307 by 2022, and is predicted to rise further to 44,085 units by 2024 upon completion of the PSN road. This represents a 3.42% increase from 2013 to 2022, followed by a 1.08% rise in 2024. The average number of branches at each intersection was 3.097 in 2013, increasing to 3.109 in 2022, with predicted to rise further to 3.123 by 2024.

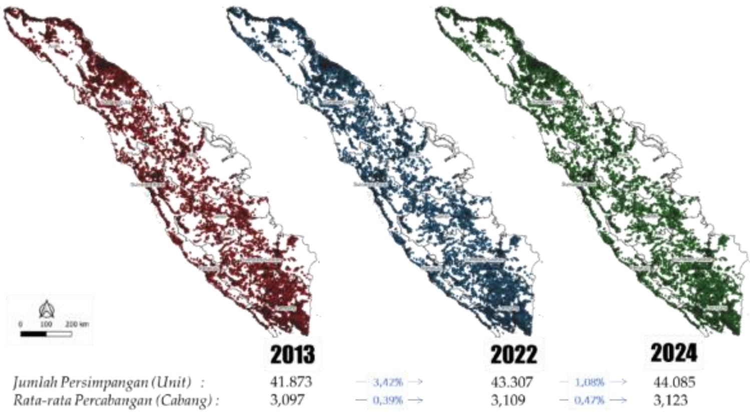

Figure 4. The processing of road network data for SDNA

The Relationship between Night-Time Light Imagery (NTL) and Gross Domestic Regional Product (GDRP)

NTL represents light intensity captured by satellites during nocturnal hours. NTL finds its appropriate application across various research domains, ranging from urban morphology (Afrianto et al., 2023), city size analysis (Ding et al., 2022), assessment of urban vitality (Zhou et al., 2023), and evaluation of urban diversification (Zhang et al., 2022). The intensity of light in NTL images correlates significantly with economic indicators such as GRDP (Afrianto, 2022). The higher the level of human activity, the higher the intensity of light captured in the NTL images. Additionally, higher levels of human activity are typically accompanied by a stronger economy. Therefore, NTL serves as a proxy for GRDP. It offers a spatial visualization of regional economic dynamics. Unlike GRDP data, which is typically tabular, NTL data is raster-based and easily spatialized.

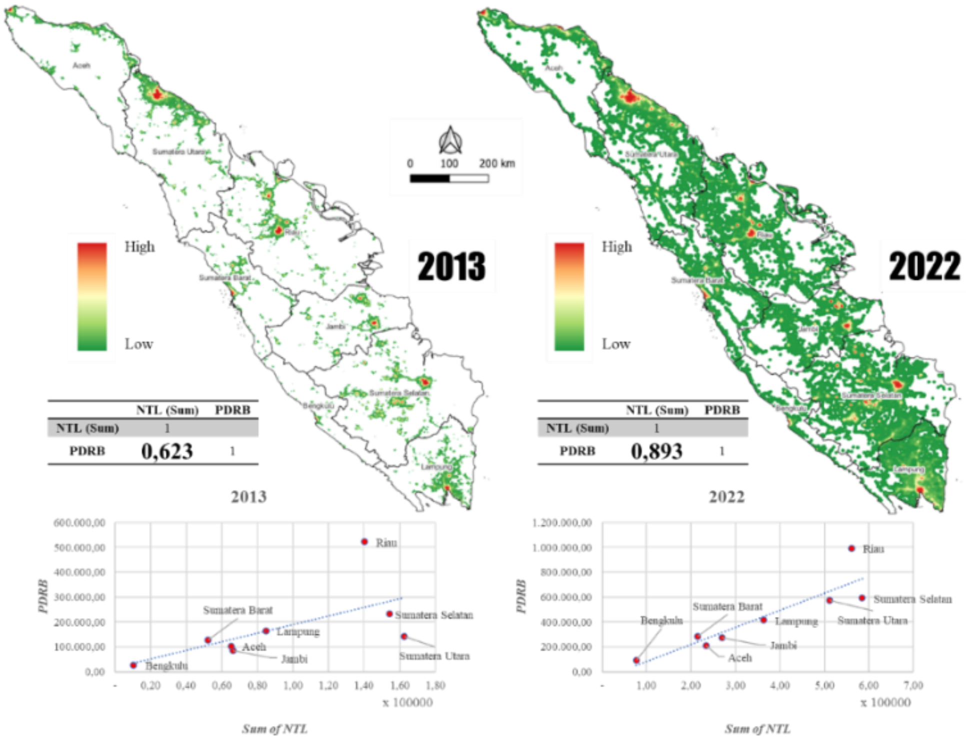

Figure 5. Night-time light (NTL) imagery and its correlation with GDRP

Figure 5 displays the NTL imagery of Sumatra Island in 2013 and 2022. In the 2013 image, high light intensity is only confined to urban centers within each province. However, in 2022, the NTL image indicates a significant increase in light intensity across the entire Sumatra Island, no longer concentrated in a single urban point in each province.

The structure of GRDP across Sumatra Island shows minimal change between 2013 and 2022. The Province of Riau consistently records the highest GRDP, while Bengkulu exhibits the lowest. These GRDP values correlate positively with the NTL light intensity across Sumatra Island. The correlation coefficients between NTL imagery and GRDP reflect a significant increase, rising from 0.623 in 2013 to 0.893 in 2022. Therefore, NTL imagery can serve as a spatial proxy for economic activity and can be effectively integrated into further road network analyses to evaluate the degree of their relationship.

The Relationship between Road Networks and Night-Time Light Imagery (NTL)

This study employs NTL as a spatial proxy to represent the economic indicator of GRDP. The relationship analysis on road networks includes their characteristics (number of road segments, length, intersections, and average branching ratio) and the network characteristics analyzed through space syntax.

Initially, the investigation focuses on the correlation between road network characteristics and NTL. The road network characteristics shows a strong correlation with NTL, which serves as a proxy for the economic sector. Before the construction of the Trans-Sumatra Toll Road in 2013, the total road length exhibited the strongest association with economic activity. However, by 2022, this relationship had shifted, with the average branching ratio emerging as the attribute most closely linked to economic activity.

Table 2. Road network's correlation with NTL in 2013

	Number of Segments	Road Length	Number of Intersections	Average Branching Ratio	NTL (Sum)
Number of segments	1				
Road length	0,947	1			
Number of intersections	0,999	0,937	1		
Average Branching Ratio	0,386	0,579	0,353	1	
NTL (Sum)	0,763	**0,906**	0,746	0,787	1

Source: Researcher (2023)

Table 3. Road network's correlation with NTL in 2022

	Number of Segments	Road Length	Number of Intersections	Average Branching Ratio	NTL (Sum)
Number of segments	1				
Road length	0,944	1			
Number of intersections	0,999	0,935	1		
Average Branching Ratio	0,551	0,735	0,526	1	
NTL (Sum)	0,642	0,830	0,623	**0,938**	1

Source: Researcher (2023)

The second relationship is between network characteristics and NTL. There are differences in the relationship between 2013 and 2022 as presented in Table 4 and Table 5. Prior to the construction of the toll road in 2013, the gravity algorithm (network attraction) and betweenness (road loading) demonstrated the strongest correlations with economic activity. However, by 2022, following the toll road completion, connectivity and accessibility emerged as the most strongly related factors. The correlations between SDNA algorithms and NTL values are presented in the tables below.

Table 4. SDNA result's correlation with NTL in 2013

	Connectivity	Closeness	Gravity	Betweenness	NTL (Sum)
Conn	1				
Closeness	-0,640	1			
Gravity	0,399	-0,595	1		
Betweenness	0,414	-0,726	0,539	1	
NTL (Sum)	0,538	-0,673	**0,866**	**0,707**	1

Source: Researcher (2023)

Table 5. SDNA result's correlation with NTL in 2013

	Connectivity	Closeness	Gravity	Betweenness	NTL (Sum)
Conn	1				
Closeness	-0,626	1			
Gravity	0,608	-0,593	1		
Betweenness	0,223	-0,621	0,146	1	
NTL (Sum)	**0,719**	**-0,749**	**0,754**	0,593	1

Source: Researcher (2023)

The correlation between SDNA algorithms and NTL, which serves as an economic proxy, shows a strong relationship both in 2013 and 2022. All algorithms have values above 0.6 except for connectivity in 2013 and betweenness in 2022. The negative values of closeness indicate an inverse relationship with NTL, consistent with closeness analysis where lower closeness values indicate higher accessibility and tighter integration. This strong relationship can be used to depict the NTL values or economic sector proxy (PDRB) in the SDNA results for 2024.

DISCUSSION

Spatial Design Network Analysis (SDNA)

The road network analysis was conducted using SDNA. The road network in Sumatra shows an increasing connectivity value (Figure 6) from 2013 to the projected year of 2024 upon the completion of the PSN. The highest connectivity value, indicated in red, is observed in the 2024 network, connecting Sumatra Island from Lampung to Aceh into a single network. Meanwhile, the provinces of West Sumatra and Bengkulu only have lateral red connecting lines without directly being linked to the main roads.

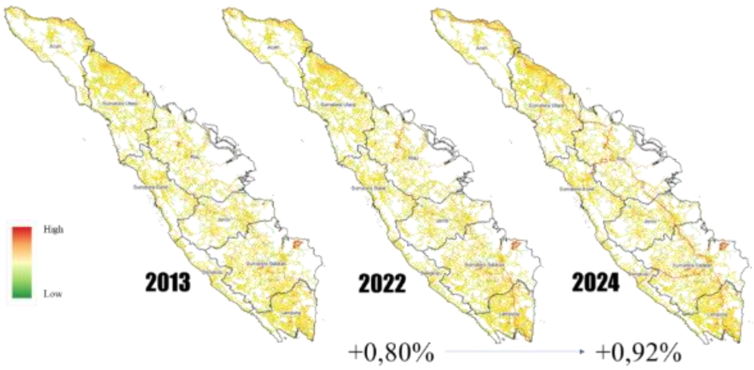

Figure 6. The connectivity of the road network in Sumatra Island

Table 6. The connectivity of the road network in Sumatra Island

Province	Connectivity in Years		
	2013	2022	2024
North Sumatra	4,072	4,115	4,154
Jambi	4,007	4,007	4,035
Bengkulu	4,025	4,041	4,083
West Sumatra	4,104	4,104	4,135
Aceh	4,001	4,024	4,078
South Sumatra	4,082	4,111	4,150
Riau	4,137	4,181	4,249
Lampung	4,019	4,121	4,121
Sumatra Island	4,056	4,088	4,126

Source: Researcher (2023)

The connectivity values of the road network in Sumatra Island (Table 6) show an average of 4.056 in 2013, 4.088 in 2022, and 4.126 in 2024. Connectivity growth is observed at 0.8% in 2022 and 0.92% in 2024. This increase indicates that the development of the Trans-Sumatra Toll Road has successfully enhanced connectivity between regions. The Province of Riau is projected to reach the highest connectivity value, i.e. 4.249, in 2024.

The closeness values of accessibility in Sumatra Island are presented in Figure 7. Unlike other syntax algorithms, the closeness value indicates the opposite; the lower the closeness value, the better the accessibility of the region. The significant construction of the PSN toll roads has effectively increased the accessibility value of Sumatra Island by 10.44% in 2022 and 146.27% in 2024 when all sections are completed.

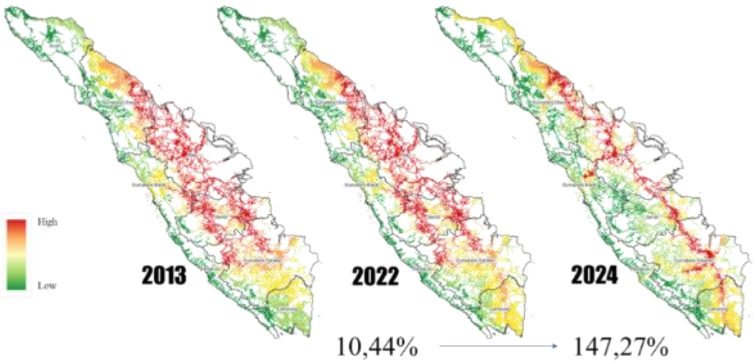

Figure 7. The closeness of the road network in Sumatra Island

Table 7. The closeness of the road network in Sumatra Island

Province	**Closeness in Years**		
	2013	**2022**	**2024**
North Sumatra	71.398,26	5.001,83	23.568,59
Jambi	65.173,26	60.600,46	30.317,98
Bengkulu	40.592,06	98.462,02	45.251,80
West Sumatra	73.851,14	68.503,04	27.997,87
Aceh	101.226,72	93.226,74	36.347,07
South Sumatra	68.891,93	63.303,00	22.348,56
Riau	58.871,83	52.638,43	19.181,38
Lampung	82.330,36	65.366,29	24.334,85
Sumatra Island	78.291,944	70.887,727	28.668,512

Source: Researcher (2023)

Table 7 shows the closeness values of the provincial road networks in Sumatra Island. Significant changes in closeness values are notable between 2013 and 2024. The average closeness value in Sumatra Island was 78.291 in 2013, significantly decreasing to 28.668 in 2024, indicating an increase in accessibility. The province with the largest increase in accessibility value is Aceh, while Lampung has the highest percentage increase in accessibility value.

The gravity values of the road network in Sumatra Island (Figure 8) indicate the concentration and the network's ability to attract movement, with the highest values observed in the provinces of Lampung, South Sumatra, and North Sumatra. Based on location, there is no changes in the structure of gravity attraction in 2013, 2022, and 2024; however, changes in gravity are evident due to an increase in gravity values. There is a 29.01% increase from 2013 to 2022, and a significant increase occurs upon the completion of the PSN, with a value of 92.03% from 2022 to 2024.

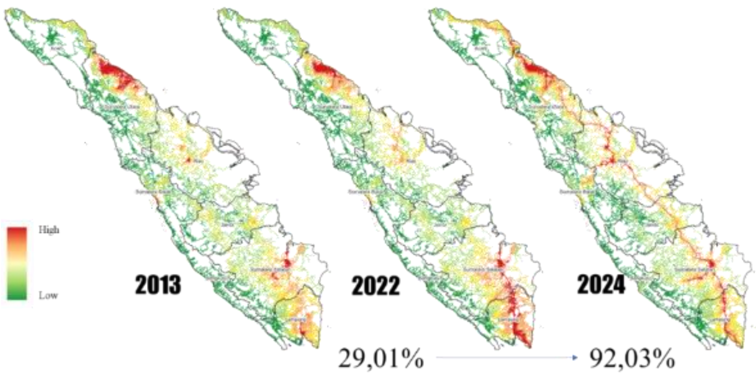

Figure 8. The gravity of the road network in Sumatra Island

Table 8. The gravitation of the road network in Sumatra Island

Province	**Gravitation in Years**		
	2013	**2022**	**2024**
North Sumatra	3,411	4,390	7,52
Jambi	1,844	2,026	4,31
Bengkulu	1,097	1,190	2,55
West Sumatra	1,981	2,076	4,36
Aceh	1,625	1,773	4,41
South Sumatra	2,471	3,528	6,13
Riau	2,225	2,753	6,86
Lampung	2,374	4,230	6,05
Sumatra Island	2,128	2,746	5,273

Source: Researcher (2023)

Table 8 shows a significant increase in the gravity attraction values occurring in each province. The average gravity value in Sumatra Island was 2.128 in 2013, increasing to 2.746 in 2022. The gravity value is predicted to increase to 5.273 in 2024 when the PSN road network is completed. The high correlation between the SDNA gravity algorithm and the NTL proxy PDRB suggests that when the gravity value increases significantly, a significant economic improvement is also predicted to occur in 2024.

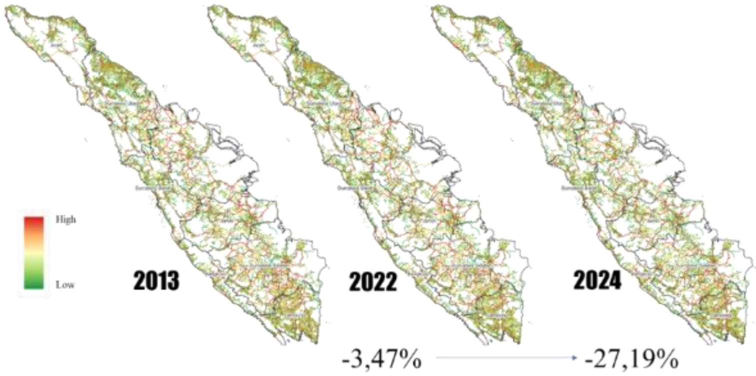

Figure 9. The betweenness of the road network in Sumatra Island

The betweenness value identifies the pathways that are most frequently chosen when moving from one point to another within a network. A high betweenness value signifies that the network traffic flow is concentrated along specific road segments, whereas a low betweenness value indicates more evenly distributed network traffic for traveling. In Sumatra Island, betweenness values exhibit a modest decline of 3.47% in 2022 and a substantial decrease of 27.19% by 2024. This decrease indicates a more equitable distribution of traffic across the road network and highlights the emergence of alternative routes following the completion of toll roads. The reduced betweenness values suggest enhanced connectivity and accessibility options for travelers in Sumatra Island.

Table 9. The betweenness of the road network in Sumatra Island

Province	**Betweenness in Years**		
	2013	**2022**	**2024**
North Sumatra	862,122	727,242	533,503
Jambi	795,000	814,302	394,560
Bengkulu	121,674	121,872	141,021
West Sumatra	377,242	377,191	347,301
Aceh	533,624	548,622	309,655
South Sumatra	582,894	526,042	407,232
Riau	940,412	958,769	777,871
Lampung	218,670	203,954	203,648
Sumatra	553,955	534,749	389,349

Source: Researcher (2023)

Table 9 shows that the average betweenness value in Sumatra Island in 2013 was 553.955, which changed to 389.349 in 2024. The most significant change occurred in the Province of Jambi, with a difference of 400.440 between 2024 and 2013.

Economic Agglomeration Analysis

The Trans-Sumatra Toll Road project offers an intriguing case study of the external impacts of infrastructure development on economic agglomeration. Utilizing fractal dimension analysis, this research measures agglomeration tendencies among economic centers, revealing that greater distances between road intersections imply stronger economic clustering. The findings suggest a gradual growth of economic agglomeration as the Trans-Sumatra project progresses.

The pre-construction measurements in 2013 indicated a maximum agglomeration scale of 1,417.68 meters. This scale expanded to 2,240.97 meters by 2022 during the project's active phase and is anticipated to leap to 3,546.65 meters by 2024 following completion. The fractal dimension is instrumental in quantifying the irregularity and pattern repetition within the road network, although it does not visually depict spatial consolidation. To address this issue, the study employs DBSCAN, which elucidates the diffusion and density of economic activities at these intersections.

In 2013, economic activities were concentrated around major cities such as Medan, Padang, Palembang, and Bandar Lampung. By 2022, significant changes were noted. Medan, Bandar Lampung, and Padang experienced expanded economic zones, whereas Palembang showed a reduced agglomeration, shifting from a primary to a medium-sized center while still continuing to grow locally.

Projections for 2024 indicate that Medan could consolidate its position as a dominant economic hub, influencing over a vast region. This indicates how enhanced connectivity via the Trans-Sumatra Toll Road could catalyze the emergence of new economic centers. Meanwhile, cities like Padang, Bandar Lampung, and Palembang are expected to maintain their economic significance but realign as medium-tier centers, with broadened spheres of economic activity reaching adjacent areas. This highlights the toll road's role in redistributing economic concentration across Sumatra.

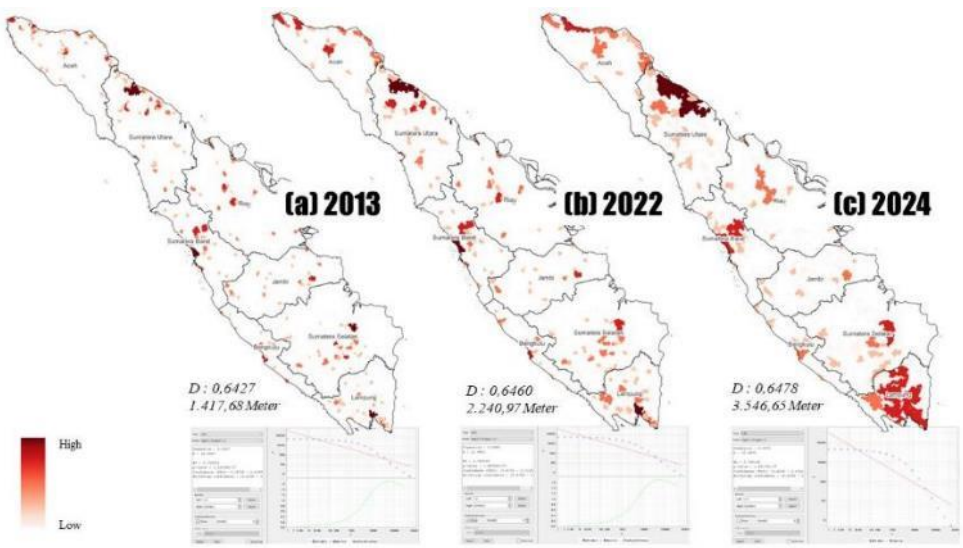

Figure 10. Economic agglomeration process in Sumatra (a) 2013; (b) 2022; (c) 2024 (100% completion of the Trans-Sumatra toll road)

The Trans-Sumatra Toll Road exemplifies the transformative power of road infrastructure on economic agglomeration. As a vital conduit for movement, it reshapes the geographical canvas of Sumatra Island, enhancing economic integration and fostering development. The emergence and enlargement of economic centers highlight the role of the roads in triggering regional economic dynamics, while also posing the challenge of managing these transitions to ensure equitable and sustainable growth across the island.

The study probes deeper than mere predictions for 2024; it endeavors to anticipate the zenith of economic agglomeration patterns that the Trans-Sumatra Toll Road might engender. As presented in Figure 11, the study predicts a future where the economic landscape reaches a state of heightened concentration at two further points: 5,556.74 meters and 8,706.08 meters, as foreseen by fractal dimension extrapolations post-2024. These projected distances suggest increasingly expansive economic clusters, extending well beyond the immediate surroundings of the toll road itself.

Using fractal dimension predictions to inform the DBSCAN analysis, the research forecasts a model for understanding how Sumatra's economic terrain could evolve with the road's completion. This prospective analysis is not just academic; it holds practical implications for policy-makers and stakeholders, preparing them for the possible ripple effects of infrastructural investments and enabling informed decisions that can steer economic activity toward the most beneficial outcomes for Sumatra Island's people and its economy.

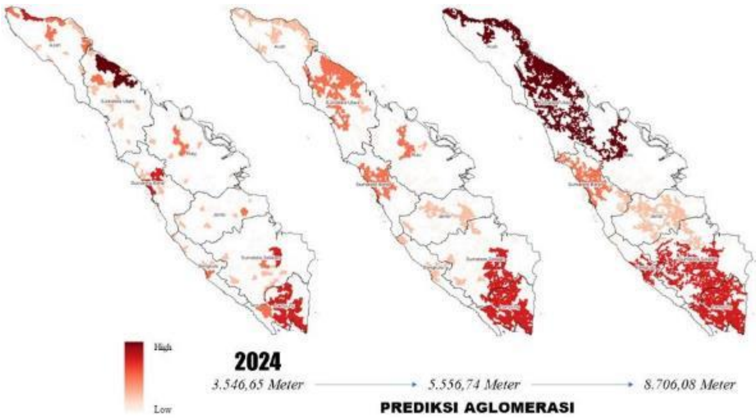

Figure 11. Long-term economic agglomeration prediction in Sumatra

The development of the Trans-Sumatra Toll Road signifies a transformative shift in Sumatra's economic geography, as it drives major shifts in economic agglomeration across the island. With the economic agglomeration scale expanding to 5,556.74 meters, there is a notable migration of the economic center from PKSN Kota Medan to PKN Bandar Lampung. Despite its categorization as a medium concentration area, the economic influence of Bandar Lampung significantly extends to Palembang and surrounding areas, thereby marking an unprecedented inter-provincial economic agglomeration.

As the economic agglomeration scale reaches its peak at 8,706.08 meters, the economic focus shifts back towards PKSN Kota Medan, which enhances economic intensity and extends its influence across Riau and Aceh. This development outlines the emergence of four principal economic agglomeration zones in Sumatra: North Sumatra, Aceh, and Riau as the primary zone; Lampung, South Sumatra, and Bengkulu as the second; West Sumatra as the third; and Jambi, marginally extending into adjacent regions, as the fourth. These shifts show the crucial role of the Trans-Sumatra Toll Road in reshaping regional economic patterns and suggest a future where improved infrastructure could redefine Sumatra's economic landscape and enhance regional connectivity and development.

Analysis of Economic Activity Intensity

NTL data is used in this study as an innovative proxy to infer the GRDP of Sumatra and offer insights into the region's economic activity. This approach enables an analysis of the relationship between the characteristics of the road network and economic vitality, particularly in the context of the construction of the Trans-Sumatra Road. The concept of "economic agglomeration" is central to this analysis, referring to the concentration of economic activities within a certain area that not only serves as an economic hub but also boosts surrounding economic growth.

Before the construction of the Trans-Sumatra Road in 2013, the economic activity in Sumatra was mainly concentrated in key urban areas, as indicated by an NTL-based economic intensity value of 628,014. However, during the construction by 2022, there was a substantial increase in economic activity to 2,404,380, which accounts for a growth of 282.85%. This remarkable rise is attributed to the activation of areas that previously exhibited low economic activity, alongside the expansion of existing economic centers. Notably, new economic hubs also emerged and contributed to the overall uplift.

Looking ahead to the expected completion of the Trans-Sumatra Road in 2024, the intensity of economic activity in Sumatra is projected to reach 3,283,260, which would represent a 36.55% increase from 2022 levels. The most significant expansion is anticipated along the eastern corridor, from Aceh to North Sumatra, and across the Lampung region, with the least growth projected for Bengkulu. These findings reveal the transformative influence of the Trans-Sumatra Road and its potential to stimulate widespread economic development and reconfigure the economic landscape of Sumatra.

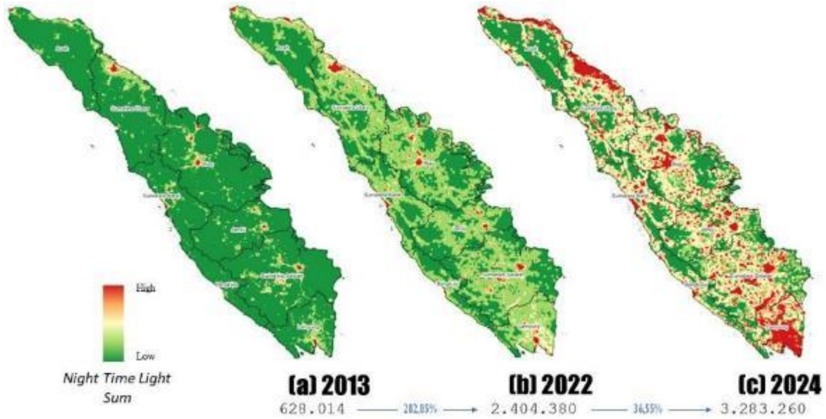

Figure 12. Dynamics of economic activity intensity in Sumatra (a) 2013; (b) 2022); (c) 2024 (100% completion of the Trans-Sumatra toll road)

This study goes further by attempting to forecast and predict the intensity of economic activity in Sumatra until the periods of 2035 and 2045. This prediction provides a deeper insight into how the economic activity patterns in Sumatra may evolve over time using linear programming. Over that time span, it appears that despite the emergence of new economic centers, the characteristic of strong agglomeration seems to be diminishing. The emerging pattern indicates a significant spread in economic intensity across various regions, thus creating a more diversified pattern.

The spatial depiction of this prediction indicates that despite some changes, the core of the economic activity pattern, which tends to be centralized, remains intact. The eastern corridor from Aceh to North Sumatra continues to be the focal point of economic activity, demonstrating continuity in its development. Additionally, a similar pattern persists in the overall Lampung region. However, it is important to note that this prediction also reflects a diversity in the distribution of the economy in Sumatra, indicating broader dynamics and shifts in the island's economic structure in the long term.

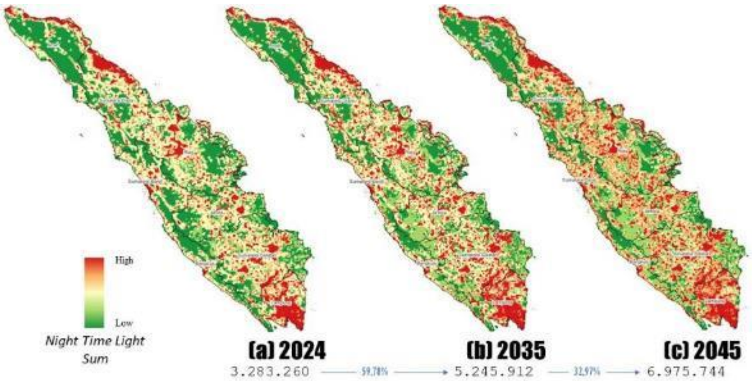

Figure 13. Predictions of Economic Activity Intensity in Sumatra (a) 2024; (b) 2035; (c) 2045

CONCLUSION

The research has successfully quantified the indirect impacts of the Trans-Sumatra Toll Road construction, focusing on spatial economic dynamics across cities and regions in Sumatra Islands. It has discussed changes in accessibility and connectivity, and forecasted the dynamics of economic agglomeration and activity intensity. Notably, the study highlights several positive and negative externalities of the toll road construction, including a predicted 3.5% increase in road intersections by 2024, and a strong correlation between NTL imagery and the GRDP. It suggests the potential of NTL as a reliable indicator of economic activity.

Additionally, the analysis noted an increase in connectivity and network centers, with a 1.72% rise in the degree of centrality, indicating growth in the road network and emergence of new network centers that boosts connectivity particularly in South Sumatra-Bengkulu and other regions. The research also highlighted a significant increase in gravitational attraction along the toll road, which suggests enhanced economic appeal.

The study observed a decrease in existing network load by about 15.33% by 2024, reflecting less congestion due to the new toll road. Closeness (accessibility) is projected to increase by approximately 78% in 2024, enhancing accessibility across the island, though Aceh and the western coastal areas show lower improvements due to centralization in the eastern region. Significant changes in economic agglomeration patterns are evident, with Medan and its vicinity remaining central to economic activity through 2024. Beyond this, Sumatra is predicted to evolve into four major agglomeration regions. Changes in economic activity centers indicate that while there is a surge in economic activity peaking by 2024, a slowdown is expected by 2035-2045, suggesting a stabilization in economic activity levels but concentrated mainly along the eastern corridor.

In response to these findings, we propose several policies to enhance Sumatra's regional economy, including continued investment in road infrastructure to connect economically potent areas, development of regional economic centers, and enhancement of multimodal transport connectivity to bolster goods and people mobility. Regions with increased gravitational attraction need to diversify their economic potentials and develop infrastructure for transit hubs. Furthermore, we recommend improving accessibility by strategically planning new network interchanges and investing in supporting infrastructure. In regions projected to experience a decline in economic concentration, it is advisable to implement economic stimuli to sustain their economic contributions. Finally, anticipating future economic agglomeration patterns necessitates inter-provincial cooperation and integrated regional spatial planning to enhance connectivity and mitigate disparities across Sumatra.

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ACKNOWLEDGEMENTS

We extend our sincere gratitude to PT Sagamartha Ultima Indonesia for their invaluable support during the preparation of this journal article. Their insights and expertise in spatial planning have greatly enriched our research and enhanced the depth of our analysis. The collaboration with their dedicated team was instrumental in achieving a comprehensive exploration of the themes addressed in our study. We are thankful for the opportunity to work with such esteemed professionals and look forward to future collaborations.

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