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Analysis of Road Network Connectivity and Efficiency in the SEI Kepayang Barat Subdistrict

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Abstract

The road network is a crucial component of a regional transportation system, supporting population mobility, the distribution of goods and services, and interregional connectivity, particularly in rural areas. This study aimed to analyze the efficiency and connectivity of the road network in Sei Kepayang Barat District, Asahan Regency, using a transportation network index approach. The methods employed included the Detour Index to measure route efficiency, Network Density to assess network density, and the Beta Index, Alpha Index, and Gamma Index to evaluate the level of connectivity and complexity of the road network. Road network data and village administrative boundaries were processed using a Geographic Information System (GIS) and analyzed quantitatively and comparatively across villages. The results showed that most villages had relatively good route efficiency, with Detour Index values ranging from 0.8 to 0.9, indicating that actual travel distances were close to straight-line distances. However, Sei Jawi-Jawi Village exhibited a higher Detour Index value (1.3), despite having the highest network density, confirming that network density was not always directly proportional to route efficiency. In terms of connectivity, Sei Kepayang Kiri Village and Sei Serindan Village demonstrated the most balanced network performance, with Beta Index values of 1.5, Alpha Index values of 0.37, and Gamma Index values of 0.59, whereas other villages exhibited simpler network structures with limited alternative routes. Overall, this study demonstrated that route efficiency, network density, and connectivity were interrelated dimensions but did not always develop linearly. Therefore, rural road network development should emphasize improving connectivity in addition to increasing road network length.

INTRODUCTION

The road network is a key element of a regional transportation system, playing a crucial role in supporting population mobility, the distribution of goods and services, and interregional connectivity (Kobilov, 2022; Patrakova, 2025; Tsonkov & Petrov, 2026). From a transportation geography perspective, the quality of a road network is determined not only by the physical availability of infrastructure but also by its efficiency and connectivity in supporting spatial movement (Susanto et al., 2024; Smith, 2025). An efficient and well-connected road network can reduce distance barriers, lower transportation costs, and improve regional accessibility, particularly in rural areas where socioeconomic activities are highly dependent on the reliable operation of land transportation systems (Johnson & Lee, 2022; Rahman, 2024).

Sei Kepayang Barat District, Asahan Regency, is a rural area characterized by a high dependence on village road networks as the primary connections between settlements, agricultural areas, and service centers (Armansyah & Sugiarto, 2024; Jihan & Anggraini, 2024; Sarifuddin & Akbar, 2024). Based on existing road network conditions in this area, several fundamental challenges remain, including uneven road network distribution, limited network density in certain areas, and network structures that tend to be linear with limited alternative routes (Susanto et al., 2024; Widodo, 2023). These conditions result in relatively low network connectivity and increase the vulnerability of the transportation system, as disruptions to a primary road segment can significantly affect overall community mobility (Chen, 2021; Smith, 2025).

These issues demonstrate the need for an analytical approach capable of quantitatively and comprehensively identifying road network conditions in terms of both travel efficiency and connectivity structure (Susanto et al., 2024; Kumar, 2024). One relevant and widely applied approach in transportation geography research is network index analysis (Smith, 2025; Kumar, 2024). This approach provides an objective assessment of road network performance through mathematical parameters and network graph measurements, thereby supporting the evaluation and planning of transportation infrastructure development in rural areas (Aburukba & El Fakih, 2025; Cao & Shahraki, 2023; Liu & Liu, 2025; Madhu et al., 2024; Marian et al., 2025; Peranginangin, 2024; Rezvani et al., 2024; Wang et al., 2022).

Theoretically, road network efficiency can be analyzed using the Detour Index, which compares the actual travel distance through a road network with the straight-line distance between locations, thereby reflecting route deviation levels (Chen, 2021; Dayalan, 2020). Road network density can be measured using Network Density, which represents the ratio between the total road network length and the area of a region (Susanto et al., 2024; Widodo, 2023). Regarding connectivity and network structure complexity, the Beta Index is used to assess the relationship between the number of road segments and nodes, while the Alpha Index measures network cycles or the availability of alternative routes. In addition, the Gamma Index evaluates road network connectivity by comparing the number of existing road segments with the maximum possible number of segments in a planar network, providing an overview of overall connectivity levels (Smith, 2025; Kumar, 2024).

Based on the research background and theoretical framework, this study aimed to analyze the connectivity and efficiency levels of the road network in Sei Kepayang Barat District, Asahan Regency, using a transportation network index approach consisting of the Detour Index, Network Density, Beta Index, Alpha Index, and Gamma Index (Susanto et al., 2024; Pratiwi, 2023). This study was expected to reveal the characteristics of the existing road network, identify network limitations and development opportunities, and provide a basis for planning and developing more effective, equitable, and sustainable road infrastructure to improve regional accessibility and support community socioeconomic activities (Smith, 2025; Johnson & Lee, 2022).

The urgency of this research was emphasized by the direct relationship between road network quality and local socioeconomic conditions. Limited connectivity can increase travel times, raise logistical costs for agricultural products, and restrict access to essential services, including healthcare and education. Therefore, a detailed assessment of existing road networks is not merely an academic exercise but also an essential prerequisite for effective and equitable infrastructure planning. The novelty of this study lies in its comprehensive multi-index analysis conducted at the village level within Sei Kepayang Barat District, providing a detailed comparative evaluation of road network connectivity and efficiency that may serve as a reference for similar rural areas in Indonesia.

This research aimed to analyze the connectivity and efficiency levels of the road network in Sei Kepayang Barat District, Asahan Regency, using a transportation network index approach involving the Detour Index, Network Density, Beta Index, Alpha Index, and Gamma Index. The primary objective was to identify the operational characteristics of the existing road network, evaluate its strengths and limitations, and highlight potential areas for improvement. The study was expected to contribute as a scientific basis for planning and developing more effective, equitable, and sustainable road infrastructure. Ultimately, the findings aimed to improve regional accessibility and support the socioeconomic activities of local communities.

METHOD

Research Location

This study was conducted in Sei Kepayang Barat District, Asahan Regency, North Sumatra Province, located at 2°57′34.19″ N latitude and 99°50′23.86″ E longitude. The study area was selected due to its rural characteristics and high dependence on the road network as the primary means of population mobility and economic activity distribution.

Data collection technique

(GIS) software. data collection includes mapping network road, identification nodes and segments roads (edges), as well as measurement long section road and distance between point. Measurement distance current done based on network road existing, whereas measurement distance straight done use Euclidean distance approach.

Data used in study This consists of on spatial data and nonspatial data. Spatial data covering map network roads and administrative boundaries West Sei Kepayang District which was obtained from source digital maps, such as OpenStreetMap and geospatial data agency related. Nonspatial data covering the area of sub-districts and villages sourced from from publication official government regions and the Central Statistics Agency. All of the data used as base in compilation network graphs and calculations index network transportation.

Data Analysis Techniques

Data analysis techniques are carried out in a way quantitative use four index network transportation, namely Detour Index, Network Density, Beta Index, and Alpha Index. Analysis efficiency network road done using the calculated Detour Index with formula:

$$\boldsymbol{DI = \frac{D_a}{D_l}}$$

where (Da) is distance travel current through network road and (Dl) is distance straight between two points. A Detour Index value approaching 1 indicates level efficiency the journey is getting longer Good.

Analysis density network road done using Network Density with formula:

$$\boldsymbol{ND = \frac{L}{A}}$$

where (L) is total network length road and (A) is the size of the study area . More Network Density value tall show level density network a better way Good in serving the area.

Analysis level connectivity network road done using Beta Index with formula:

$$\boldsymbol{\beta} = \frac{\boldsymbol{E}}{\boldsymbol{V}}$$

where (E) is amount section road and (V) is amount node. The Beta Index value is used For evaluate level connectedness between knot in network road.

Next, analysis complexity structure network done using the calculated Alpha Index with formula:

$$\boldsymbol{\alpha} = \frac{\boldsymbol{E - V + 1}}{\boldsymbol{2V - 5}}$$

Alpha Index is used For measure level existence cycle or track alternative in network road. The Alpha Index value ranges from between 0 to 1, where value approaching 0 indicates network that is simple and linear, whereas mark approaching 1 indicates an increasingly network complex.

In addition, the level of connectedness network road in a way overall analyzed using the Gamma Index with formula:

$$\boldsymbol{\gamma} = \frac{\boldsymbol{E}}{\boldsymbol{3(V - 2)}}$$

Where$E$ is amount section roads and $V$is the number of nodes. The Gamma Index is used to assess the proportion of road network connectivity to the maximum condition of a planar network. A Gamma Index value close to 1 indicates a high level of network connectivity, while a low value indicates limited connectivity and a lack of alternative routes in the road network.

The results of the calculation of the four indexes were then analyzed descriptively and comparatively between villages in Sei Kepayang Barat District, and interpreted based on the network concept in transportation geography to assess the level of connectivity and efficiency of the road network in the research area.

RESULTS AND DISCUSSION

Sei Kepayang Kiri Village

Figure 1. Graphical Representation Map of Straight Roads in Sei Kepayang Kiri Village
Source: Data Analysis Results, 2025

Figure 2. Original Road Network Map of Sei Kepayang Village, Kiri
Source: Data Analysis Results, 2025

Table 1. Length of the Sei Kepayang Kiri Village Road Network

Road Type/Graph	Length (km)
Straight Graph Path	12.3
The Real Way	12.5

Source: Data Analysis, 2025

Based on the data on the map and table above, a calculation analysis using the five methods was conducted to find that the road network in Sei Kepayang Kiri village shows that the road network in the study area has relatively good route efficiency, but network connectivity and complexity are still limited. A Detour Index value of 0.8 indicates that the actual travel distance is close to a straight distance, in accordance with the characteristics of rural areas with low geographic barriers (Black, 2003; Rodrigue, 2013).

A Network Density of 4 km/km² indicates a fairly adequate road network, although its distribution is uneven and still concentrated in residential areas. In terms of connectivity, a Beta Index of 1.5 indicates the network has exceeded the minimum structure and has limited alternative routes.

Furthermore, the Alpha Index of 0.37 and Gamma Index of 0.59 indicate that the network's complexity and connectivity are moderate. This finding aligns with the general characteristics of rural road networks, which emphasize basic connection efficiency over complex network formation.

Sei Serindan Village

Figure 3. Graphical Representation Map of Straight Roads in Sei Serindan Village
Source: Data Analysis Results , 2025

Figure 4. Original Road Network Map of Sei Kepayang Village, Kir i
Source : Data Analysis Results, 2025

Table 2. Length of the Sei Serindan Village Road Network

Road Type/Graph	Length (km)
Straight Graph Path	4
The Real Way	4.8

Data Analysis , 2025

Based on the data in the map and table above, a calculation analysis using the five methods was conducted to find that the road network in Sei Serindan village shows that the road network in the study area has relatively good route efficiency, but network connectivity and complexity are still limited. A Detour Index value of 0.8 indicates that the actual travel distance is close to a straight distance, in accordance with the characteristics of rural areas with low geographic barriers (Black, 2003; Rodrigue, 2013).

A Network Density of 4 km/km² indicates a fairly adequate road network, although its distribution is uneven and still concentrated in residential areas. In terms of connectivity, a Beta Index of 1.5 indicates the network has exceeded the minimum structure and has limited alternative routes.

Furthermore, the Alpha Index of 0.37 and Gamma Index of 0.59 indicate that the network's complexity and connectivity are moderate. This finding aligns with the general characteristics of rural road networks, which emphasize basic connection efficiency over complex network formation.

Sei Lendir Village

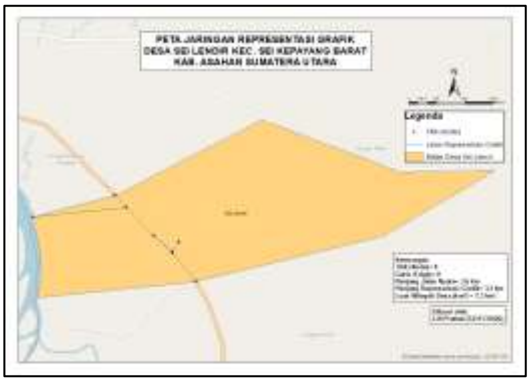

Figure 5. Graphical Representation Map of Straight Roads in Sei Lendir Village
Source: Data Analysis Results, 2025

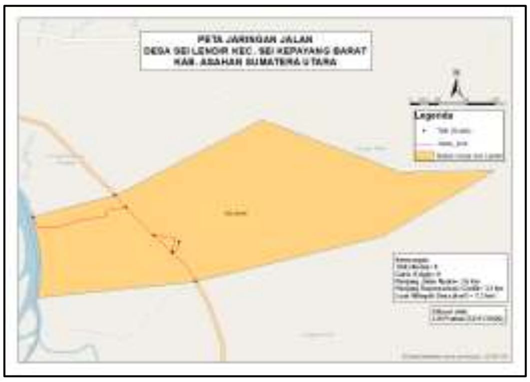

Figure 6. Original Road Network Map of Sei Lendir Village
Source: Data Analysis Results, 2025

Table 3. Length of the Sei Lendir Village Road Network

Road Type/Graph	Length (km)
Straight Graph Path	3.3
The Real Way	3.6

Source: Data Analysis , 2025

Based on the data in the map and table above, analysis using the five methods above revealed that the road network in Sei Lendir village is robust, but still limited in terms of density and connectivity. A Detour Index of 0.9 indicates that the actual travel distance is close to a straight-line distance, consistent with the characteristics of a rural area with few geographic barriers.

A Network Density value of 0.4 km/km² indicates a low road network density, resulting in uneven access distribution. In terms of connectivity, a Beta Index of 1.0 indicates the network has achieved minimum connectivity, but route flexibility remains limited.

Furthermore, an Alpha Index of 0.09 and a Gamma Index of 0.44 indicate low complexity and connectivity of the road network. This reflects a network structure that is still linear and lacks alternative routes, as is common in rural areas.

Sei Jawi-Jawi Village

Figure 7. Graphical Representation Map of Straight Roads in Sei Jawi-Jawi Village
Source: Data Analysis Results, 2025

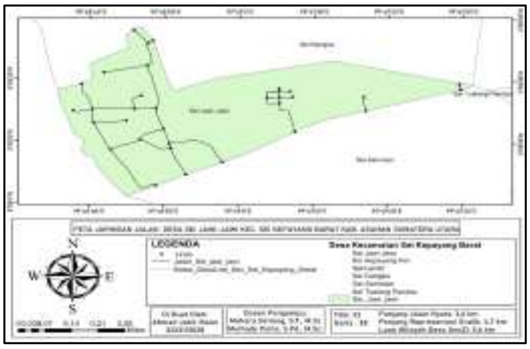

Figure 8. Original Road Network Map of Sei Jawi-Jawi Village
Source: Data Analysis Results, 2025

Table 4. Length of the Sei Jawi-Jawi Village Road Network

Road Type/Graph	Length (km)
Straight Graph Path	4.7
The Real Way	3.6

Source: Data Analysis, 2025

Based on the data in the map and table above, a calculation analysis using the five methods above shows that the road network in Sei Jawi-Jawi village shows that the performance of the road network in this area varies between route efficiency and connectivity structure. A Detour Index value of 1.3 indicates that the actual travel distance is still longer than the straight distance, but is still considered quite efficient for a rural area with a simple network pattern.

A network density of 6 km/km² indicates a high road network density, resulting in relatively good internal accessibility. However, high density does not necessarily translate into high network connectivity.

In terms of network structure, a Beta Index of 1.1 indicates a fairly good level of connectivity, while an Alpha Index of 0.049 and a Gamma Index of 0.4 indicate low network complexity and connectivity. This indicates that the road network is still linear and has limited alternative routes.

Sei Nangka Village

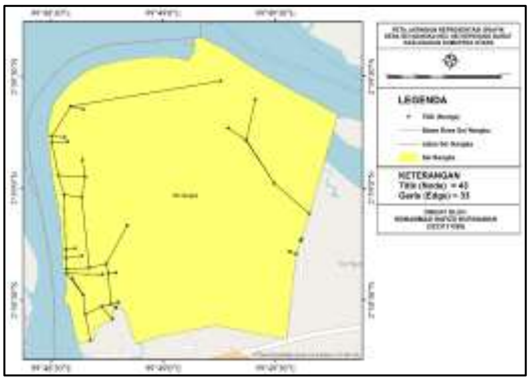

Figure 9. Graphical Representation Map of Straight Roads in Sei Nangka Village
Source: Data Analysis Results, 2025

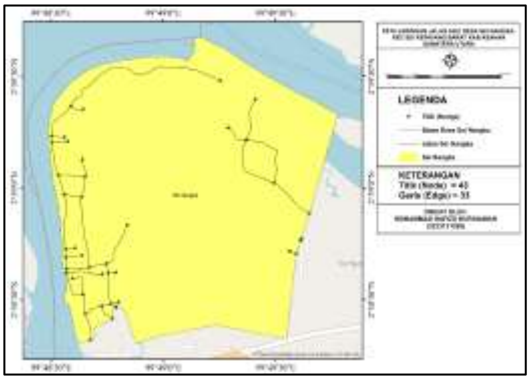

Figure 10. Original Road Network Map of Sei Nangka Village
Source: Data Analysis Results, 2025

Table 5. Length of the Sei Nangka Village Road Network

Road Type/Graph	Length (km)
Straight Graph Path	9
The Real Way	9.6

Source: Data Analysis , 2025

Based on the data in the map and table above, an analysis of the calculations using the five methods above shows that the road network in Sei Nangka village shows that the transportation network has relatively good spatial efficiency, but the level of connectivity and complexity is still low. The Detour Index value of 0.9 indicates that the distance traveled through the road network is not much different from the straight distance, so the network is quite efficient in reducing distance friction. The road network density indicated by the Network Density of 1 km/km² reflects adequate network conditions to serve basic activities in rural areas.

However, the low Beta Index (0.9), Alpha Index (0.03), and Gamma Index (0.34) indicate that the road network remains simple, with minimal alternative routes, and low redundancy. This indicates that, although the network is relatively efficient, its resilience to disruption and mobility flexibility are still limited. This pattern aligns with the general characteristics of rural transportation networks, which develop linearly and focus on connectivity between key points rather than increasing network complexity.

Sei Tualang Pandau Village

Table 6. Length of the Sei Tualang Pandau Village Road Network

Road Type/Graph	Length (km)
Straight Graph Path	3.5
The Real Way	5

Source: Data Analysis, 2025

Based on the data on the map and table above, an analysis of the calculations using the five methods above was carried out, and it was found that the road network in Tualang Pandau Village for the Detour Index (0.9) indicates that the road network in Tualang Pandau Village is classified as quite efficient, because the distance traveled through the road network is relatively close to a straight distance. This condition is in accordance with the character of the rural network which generally develops along direct routes between main points.

The Network Density value of 1.78 km/km² indicates moderate to fairly dense road network density, which shows that the road network has been able to reach most of the village area, even though it has not been developed intensively.

The Beta Index (0.29) indicates a low level of network connectivity, reflecting a simple network structure with minimal alternative routes. This finding aligns with expectations for rural areas.

An Alpha Index value of 0 indicates the absence of network cycles , so the road network remains a *tree network* . This condition indicates low redundancy and high dependence on certain road sections.

A Gamma Index value of 0.10 confirms that the road network's connectivity level is still very low compared to optimal conditions. Overall, these results indicate that while the road network is relatively efficient, its complexity and resilience are still limited.

Comparison Between Villages

Table 7. Summary of Results for Each Index in Each Village

Village	Detour Index (DI)	Network Density (km/km²)	Beta Index (β)	Alpha Index (α)	Gamma Index (γ)
Left Sea of Kepayang	0.8	4.0	1.5	0.37	0.59
Sei Serindan	0.8	4.0	1.5	0.37	0.59
Slime	0.9	0.4	1.0	0.09	0.44
Sei Jawi-Jawi	1.3	6.0	1.1	0.049	0.40
Jackfruit	0.9	1.0	0.9	0.03	0.34
Sei Tualang Pandau	0.9	1.78	0.29	0.00	0.10

Source: Data Analysis, 2025

Based on the summary table of results, it can be concluded that the most effective route efficiency is generally shown by Sei Lendir Village, Sei Nangka Village, and Sei Tualang Pandau Village, which have a Detour Index value (0.9), approaching the ideal value of one. This value indicates that the distance traveled through the road network is relatively efficient and not much different from the straight distance. This finding is in accordance with the character of rural transportation networks which generally develop directly and linearly between major points, as reported in the rural road network studies by Black (2003) and Rodrigue (2013).

In contrast, Sei Jawi-Jawi Village showed the highest Detour Index (1.3), indicating the lowest route efficiency compared to other villages. This result was relatively unexpected, considering that the village has the highest Network Density (6.0 km/km²). This condition indicates that high network density does not always directly correlate with route efficiency. This phenomenon can be explained by the network structure, which is still linear and less efficient.

integrated, so that despite the large number of road sections, their connectivity patterns are not optimal. This finding aligns with literature stating that network density without good connectivity does not automatically improve transportation efficiency.

In terms of network connectivity and complexity, Sei Kepayang Kiri and Sei Serindan villages hold the most superior positions. These two villages have the highest Beta Index (1.5) and relatively higher Alpha (0.37) and Gamma Index (0.59) values compared to other villages. This indicates that the road networks in these two villages are not only spatially efficient but also have a better level of connectivity and redundancy. These results are in line with expectations, as networks with more cycles and alternative routes tend to be more resilient to disruptions and more flexible in supporting mobility.

In contrast, Sei Tualang Pandau and Sei Nangka villages exhibit the lowest levels of network connectivity and complexity, as reflected by low Beta, Alpha, and Gamma Index values, with the Alpha Index even reaching zero in Sei Tualang Pandau. This confirms that the road network still consists of a tree network, with high dependence on specific sections and minimal alternative routes. While this finding is less than satisfactory in terms of network resilience, it is still considered reasonable and meets expectations for a rural area with limited infrastructure development.

The results of the road network index analysis in West Sei Kepayang District indicate that route efficiency, network density, and connectivity levels do not always develop in a unidirectional manner. This finding confirms that road network performance is determined not only by the length or number of road segments, but also by the structure of interconnectedness between nodes, as emphasized in transportation geography studies (Black, 2003; Rodrigue, 2013).

Most villages exhibit relatively good route efficiency, indicated by Detour Index values approaching one, particularly in Sei Lendir, Sei Nangka, and Sei Tualang Pandau. This condition aligns with the characteristics of rural transportation networks, which develop linearly and are oriented towards direct connections between activity centers (Chen, 2021; Dayalan, 2020). However, Sei Jawi-Jawi Village exhibits a discrepancy, where the highest network density is not accompanied by route efficiency, reflected in a Detour Index value of 1.3. This suggests that network density without structural integration does not necessarily improve travel efficiency (Smith, 2025; Kumar, 2024).

In terms of connectivity, Sei Kepayang Kiri and Sei Serindan villages demonstrated the most optimal network performance with relatively higher Beta, Alpha, and Gamma Index values, reflecting a more connected network and the presence of alternative routes. Conversely, Sei Nangka and Sei Tualang Pandau villages had the simplest network structures, characterized by low connectivity index values and the absence of network cycles. This pattern indicates that rural road networks are generally still oriented towards basic access efficiency, with limitations in network complexity and resilience.

CONCLUSION

The results of this study indicated that most villages had relatively good route efficiency, as reflected by Detour Index values ranging from 0.8 to 0.9, indicating that actual travel distances through the road network were close to straight-line distances. This condition reflected the general characteristics of rural transportation networks, which tend to develop linearly and prioritize direct connections between major locations. An exception was observed in Sei Jawi-Jawi Village, which had a Detour Index value of 1.3, indicating lower route efficiency despite having the highest network density.

Network Density values varied considerably among villages, ranging from 0.4 km/km² to 6.0 km/km², confirming that network density was not always directly correlated with travel efficiency. In terms of connectivity, Sei Kepayang Kiri Village and Sei Serindan Village demonstrated the most balanced network performance, with Beta Index values of 1.5, Alpha Index values of 0.37, and Gamma Index values of 0.59, reflecting relatively more connected network structures. In contrast, Sei Nangka Village and Sei Tualang Pandau Village exhibited lower network connectivity and complexity, as indicated by Beta Index values below 1, Alpha Index values ≤ 0.03, and Gamma Index values ≤ 0.34. The Alpha Index value of zero in Sei Tualang Pandau Village indicated that its road network had a tree-like structure with no circuit connections.

This study had several limitations, as it focused only on structural aspects of the road network and used static data without considering road conditions, traffic volume, or population movement dynamics. Nevertheless, this study provided an important contribution by offering a quantitative and comparative assessment of rural road network performance and demonstrating that network efficiency, density, and connectivity did not always develop linearly. Future research should integrate traffic data, road condition assessments, temporal analysis, and spatial modeling to support more efficient and sustainable rural transportation network planning.

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