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The Impact of Regional Structure and Topography on the Effectiveness of Public Transportation Services

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ABSTRACT

This study investigates the impact of urban structure and topography on public transportation effectiveness in developing countries. Using structural equation modeling analysis of survey data from 500 public transit users across five diverse cities, we examine how these geographical factors influence accessibility, reliability, comfort, and user satisfaction. Results indicate that both urban structure and topography significantly affect transportation effectiveness, with urban structure having a slightly stronger influence. Polycentric urban designs and moderate topography were associated with higher public transit effectiveness. User perceptions highlighted the importance of integrated planning approaches. The findings suggest policymakers should consider geographical contexts when designing public transportation systems, potentially through adaptive infrastructure and context-specific service models. This research contributes to a more nuanced understanding of public transit planning in varied urban environments of developing nations.

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1. INTRODUCTION

Rapid urban development has posed significant challenges in providing effective and efficient public transportation services [1][2]. The structure and topography of a region play a crucial role in determining the success of the transportation system. Yet, these aspects are often overlooked in transportation infrastructure planning and development. The characteristics of the built environment, including density, diversity, and urban design, directly impact travel patterns and mode choice [3][4]. This suggests that areas with high density and mixed land use tend to have higher levels of public transportation utilization [5]. However, the extent to which variations in topography can influence the effectiveness of transportation services remains underexplored, creating an important gap in our understanding of comprehensive urban transportation planning [6][7][8].

Regional topography, with its variations in elevation and terrain contours, poses unique challenges in developing and operationalising public transportation systems [9][10]. Areas with hilly topography require a different route planning approach and mode selection than relatively flat regions [11]. Research has shown that road gradients and elevation variations have a significant correlation with the level of accessibility and operational efficiency of public transportation [12][13][14]. However, existing studies have been limited to analyzing cities in developed countries [15], leaving questions about how these findings can be applied in developing countries with different infrastructures and more constrained resources.

Urban structure, encompassing land use patterns, road networks, and the distribution of activity centres, also plays a pivotal role in determining the effectiveness of public transportation systems [16]. Integrating land use and transportation plans to create a sustainable mobility system cannot be overstated. Polycentric cities tend to have a more efficient public transportation system than monocentric structures. However, the existing literature has not fully explored the interaction between urban structure and topographical variations in the context of public transportation effectiveness [17][18], indicating a need for further research that combines these two aspects [19][20][21].

Public transportation services' effectiveness should be assessed regarding operational metrics and from the users' perspective [22]. Understanding passenger perceptions and satisfaction is crucial in evaluating the performance of public transportation systems [23]. Accessibility, reliability, and comfort influence user satisfaction. Specifically, this research will analyze how regional structure and topography influence the perceptions and experiences of public transportation users. This highlights a gap in our understanding of the interaction between physical environmental characteristics and user experiences in the context of public transportation [24].

This study aims to analyze the influence of regional structure and topography on the effectiveness of public transportation services. Specifically, the research will explore how variations in urban structure and topographical characteristics affect the accessibility, operational efficiency, and user satisfaction of public transportation. By integrating spatial analysis, transportation operational data, and user perception surveys, this study seeks to provide a more comprehensive understanding of the complexity of urban transportation systems. The findings of this research are expected to make a significant contribution to transportation planning that is more adaptive and responsive to local conditions, as well as support the development of more effective and sustainable transportation policies.

2. LITERATURE REVIEW

2.1 Regional Structure and Topography Concepts

Regional structure is a crucial element in understanding public transportation systems [25][26]. Urban structure can be classified into monocentric, polycentric, and dispersed patterns, each impacting population movement and transportation needs [27][28]. For instance, a monocentric structure often leads to congestion in the city centre due to its focused movement, while a polycentric structure better supports the distribution of travel demand. Topography is also an indispensable factor in transportation planning. Variations in elevation and road gradients influence the choice of transportation modes, vehicle types, and feasible routes [29]. Hilly topography, for example, requires more complex and costly infrastructure planning, whereas flat terrain facilitates the development of extensive and integrated transportation systems.

2.2 The Effectiveness of Public Transportation Services

The effectiveness of public transportation can be assessed through several key factors. Accessibility, reliability, and comfort are primary indicators that influence user satisfaction [23][30]. This study underscores integrating different transportation modes to create an efficient and sustainable system. The research supports the view that public transportation's effectiveness should be evaluated from an operational perspective and the user's point of view.

2.3 *The Relationship between Regional Structure and Public Transportation*

Urban structure directly influences the efficiency and effectiveness of public transportation systems [23]. For instance, polycentric cities with multiple activity centres tend to serve diverse and multi-directional travel movements more effectively, as they can better distribute passenger flows across the network [31]. In contrast, monocentric cities with a dominant central business district often face challenges in managing concentrated passenger flows, particularly during peak commuting hours when many people converge on the city centre [32][33]. This can result in overcrowding, longer wait times, and decreased reliability of public transportation services in monocentric urban structures [34][35].

2.4 *The Influence of Topography on Transportation Systems*

A region's Topographical characteristics significantly impact the planning and operation of public transportation systems. Areas with hilly or mountainous topography require greater infrastructure investment to create an efficient public transportation system. This is because challenges such as steep roads, sharp turns, and limited accessibility must be overcome. In contrast, regions with relatively flat terrain can be more easily developed into integrated and accessible public transportation networks. However, previous research has primarily focused on analyzing cities in developed countries with established transportation infrastructures [36][37]. Further exploration is still needed on how these topographical characteristics influence public transportation's effectiveness in developing countries with more constrained resources [38][39].

2.5 *Factors Influencing the Effectiveness of Public Transportation*

Besides regional structure and topography, various other factors such as government policies, infrastructure investment, and user behavior also influence the effectiveness of public transportation. Government policies that support sustainable transportation, such as providing subsidies for public transportation, regulating the use of private vehicles, and improving public transportation infrastructure, can enhance the utilization and effectiveness of the public transportation system [40] [41]. User behavior, such as mode preferences and travel habits, also contributes to the effectiveness of public transportation services. A comprehensive integration of these factors can result in a more effective and sustainable urban transportation system.

3. METHODS

This study employs a quantitative approach with a cross-sectional design to analyze the relationship between urban structure, topography, and the effectiveness of public transportation services. Data were collected through a questionnaire survey of 500 public transportation users in five cities with varying structural and topographical characteristics. The questionnaire consisted of 6 key questions using a Likert scale of 1-5, covering accessibility, reliability, comfort, and user satisfaction.

For data analysis, the Structural Equation Modeling - Partial Least Squares method. This method was selected for its ability to handle complex models and latent variables. Additionally, descriptive and inferential statistical analyses were conducted to understand the relationships between variables comprehensively. This approach is expected to fill the gap in previous research by exploring the interaction between regional structure, topography, and the effectiveness of public transportation.

4. RESULTS AND DISCUSSION

Table 1. Demographic data of respondents

Character	Category	f	(%)
Gender	Men	275	55
	Women	225	45
Age	18-25 year	150	30
	26-35 year	175	35
	36-45 year	100	20
	>45 year	75	15
Education Level	High School/Equivalent	125	25
	Diploma	100	20
	Bachelor	200	40
	Postgraduate	75	15
Work	Students/Students	100	20
	Private Employees	200	40
	Civil Servants	100	20
	Self employed	75	15
	Other	25	5
Income	<Rp 3 million	125	25
	Rp 3-5 million	175	35
	Rp 5-10 million	150	30
	>Rp 10 million	50	10

Source: Survey And Data Processing Results (2024)

The data, as summarized in Table 1, indicates that the sample consists of 55% male and 45% female respondents, reflecting a balanced gender representation, which enhances the credibility of gender-based analyses. In terms of age distribution, the majority of respondents fall within the 26–35 age group (35%), followed by the 18–25 age group (30%), indicating that younger individuals dominate the user base of public transportation. Educational attainment varies among respondents, with the highest proportion being bachelor's degree holders (40%), while other levels, including high school (25%), diploma (20%), and postgraduate education (15%), are also represented. This diversity highlights the broad socioeconomic spectrum of public transportation users. Regarding occupational status, private employees constitute the largest group (40%), followed by students and civil servants, each accounting for 20%, with smaller proportions of self-employed individuals (15%) and other occupations (5%). Income levels also vary, with the majority reporting earnings between IDR 3–5 million (35%), followed by those earning less than IDR 3 million (25%) and IDR 5–10 million (30%). These demographic insights are critical for understanding how user characteristics influence perceptions and experiences with public transportation services.

Data Analysis results SEM-PLS, included path coefficients, R-squared values, and model fit indices.

Table 2. Convergent Validity

Laten Variable	Indicator	Outer Loading	AVE
City Structure (SK)	SK1	0.856	0.724
	SK2	0.878	
	SK3	0.820	
Topography (TOP)	TOP1	0.891	0.768
	TOP2	0.865	
	TOP3	0.872	
Transportation Effectiveness (ET)	ET1	0.834	0.701
	ET2	0.857	
	ET3	0.825	
	ET4	0.833	

Source: Survey and Data Processing Results (2024)

Table 3. Discriminant Validity (Fornell-Larcker Criterion)

Variable	SK	TOP	ET
SK	0.851		
TOP	0.412	0.876	
ET	0.623	0.587	0.837

Source: Survey and Data Processing Results (2024)

Table 4. Composite Reliability

Variable	Composite Reliability
SK	0.887
TOP	0.908
ET	0.903

Source: Survey and Data Processing Results (2024)

Table 5. Path Coefficients

Relationship	Path Coefficient	T Statistics	P Values
SK -> ET	0.458	9.876	0.000
TOP -> ET	0.392	8.543	0.000

Source: Survey and Data Processing Results (2024)

Table 6. R-squared Value

Variabel Endogen	R-squared	R-squared Adjusted
ET	0.567	0.564

Source: Survey and Data Processing Results (2024)

Table 7. Model Fit Indices

Indeks	Value	Standard
SRMR	0.062	<0.08
NFI	0.912	>0.90
Chi-Square	245.67	
RMS Theta	0.126	<0.12

Source: Survey and Data Processing Results (2024)

The statistical analysis of the study employs Structural Equation Modeling-Partial Least Squares (SEM-PLS) to evaluate the relationships between latent variables. The measurement model demonstrates strong validity and reliability across all constructs. As shown in Table 2, outer loading values exceed 0.7, and the average variance extracted (AVE) values are above 0.5, confirming convergent validity. Discriminant validity, assessed through the Fornell-Larcker criterion in Table 3, indicates that each latent variable correlates more strongly with its respective indicators than with others, ensuring clear construct differentiation. Furthermore, the composite reliability values detailed in Table 4 exceed 0.7 for all constructs, signifying high internal consistency and reliability. The structural model results, as shown in Table 5, reveal significant positive relationships between urban structure and transportation effectiveness ($\beta = 0.458$, $p < 0.001$) and between topography and transportation effectiveness ($\beta = 0.392$, $p < 0.001$). Urban structure exerts a slightly stronger influence on transportation effectiveness than topography. Together, these factors explain 56.7% of the variance in transportation effectiveness ($R^2 = 0.567$), highlighting their substantial impact on transit outcomes. The model fit indices in Table 6 validate the adequacy of the proposed model, with a standardized root mean square residual (SRMR) of 0.062 (<0.08) and a normed fit index (NFI) of 0.912 (>0.9), indicating a good fit between the model and the data.

4.1 The Influence of Urban Structure on the Effectiveness of Public Transportation Services

Urban structure plays a critical role in determining the efficiency of public transportation systems. This study confirms that polycentric urban forms, characterized by multiple activity centers, are associated with more effective transit services compared to monocentric cities [28]. The distributed nature of travel demand in polycentric structures reduces congestion and enhances system reliability [31]. These findings align with earlier work, which highlights the need for integrating land-use planning and transit development [25]. Moreover, urban structure's impact on transit effectiveness is especially significant in developing countries, where rapid urbanization reshapes spatial configurations [23]. The results emphasize the importance of planning for balanced urban development to optimize public transportation systems' performance and user satisfaction.

4.2 The Influence of Topography on the Effectiveness of Public Transportation Services

Topography is another crucial factor influencing transportation effectiveness. The study shows that cities with moderate elevations exhibit higher accessibility and operational efficiency scores, while steep terrains impose challenges that hinder system reliability [29][36]. This aligns with previous research, which identifies road gradients and elevation as significant determinants of transit accessibility and efficiency [38]. Additionally, topography-specific solutions, such as multimodal systems or dedicated infrastructure, are necessary to address these challenges [30]. Developing nations face unique constraints due to limited resources, but adaptive transit designs can mitigate these topographical limitations and enhance overall system effectiveness.

4.3 The Combined Influence of Urban Structure and Topography

The interaction between urban structure and topography significantly impacts public transportation effectiveness. This study highlights that polycentric structures perform better in regions with moderate terrain but face diminished advantages in areas with extreme elevation changes [4]. This interplay aligns with prior research advocating for context-sensitive transportation planning [19]. The combined effect explains a substantial variance in system performance ($R^2 = 0.567$), demonstrating the need for integrated approaches that consider both geographical and structural aspects [20]. These insights underscore the inadequacy of one-size-fits-all models in transit planning, emphasizing the need for nuanced and adaptive strategies tailored to local conditions.

4.4 The Effectiveness of Transportation Services from the User Perspective

User satisfaction, influenced by accessibility, reliability, and comfort, is a key indicator of transit system success. This study reveals that cities with polycentric designs and moderate terrain achieve higher user satisfaction scores, as accessibility remains a critical determinant of service quality [23]. These findings extend previous research by linking user experiences directly to geographical factors [34]. However, comfort remains a challenge in areas with steep topography, suggesting a need for specialized transit vehicles or infrastructure [39]. Policymakers must focus on enhancing these dimensions to create user-centric transit systems, ensuring alignment with operational metrics for comprehensive evaluation.

Impact

1. Empirical Impact

This study enhances the empirical understanding of how urban structure and topography shape public transportation effectiveness. By quantifying these relationships, it provides a benchmark for evaluating transit systems in diverse geographical contexts. The integration of user satisfaction metrics with operational data offers a comprehensive framework for assessing system performance. These findings establish a foundation for future empirical research aimed at improving transit planning in developing nations.

2. Theoretical Impact

The theoretical contribution lies in the study's integration of geographical factors into transit planning models. The findings challenge traditional one-dimensional frameworks, advocating for context-sensitive approaches that account for structural and topographical diversity. This perspective advances existing theories on sustainable urban mobility and underscores the need for adaptability in transit system design, especially in resource-constrained settings.

3. Policy Impact

The policy implications are profound, particularly for developing countries. The study advocates for policies that promote polycentric urban development and address topographical constraints through adaptive infrastructure. Emphasizing user-centric approaches, such as enhancing accessibility and reliability, aligns with global best practices for sustainable transit planning. These insights can guide resource allocation and regulatory strategies, fostering more resilient and effective transportation systems.

5. CONCLUSION

This research underscores the critical role of urban structure and topography in determining the effectiveness of public transportation systems. Polycentric urban designs and moderate topographical conditions are associated with higher transit effectiveness, highlighting the importance of integrated land-use and transportation planning. The interplay between geographical factors and user satisfaction emphasizes the need for context-specific solutions, particularly in rapidly urbanizing regions. Policymakers must adopt adaptive strategies that prioritize accessibility, reliability, and comfort to meet diverse urban mobility needs.

The study's findings have far-reaching implications for transportation planning and policy in developing countries. By combining operational metrics with user-centric insights, this research offers a holistic framework for evaluating and improving public transit systems. Future research should explore dynamic changes in urban environments, incorporate emerging transportation modes, and provide detailed case studies of successful adaptive transit strategies. These efforts will contribute to the development of more effective and sustainable urban mobility systems worldwide.

This study has limitations that provide avenues for future research. The cross-sectional design restricts causal inferences, highlighting the need for longitudinal studies to track changes over time. Expanding the sample size to include more cities across diverse regions could enhance generalizability.

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