MEASURING SPATIAL ADAPTABILITY ALONG BRT CORRIDORS: WHY FORM, REGULATION, AND ACCESSIBILITY MUST BE MEASURED TOGETHER

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Abstract

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The Spatial Adaptability Index (SAI) is proposed as an integrated, spatially explicit tool for assessing the transformation potential of urban areas influenced by Bus Rapid Transit (BRT) systems. Applied to Guatemala City's Transmetro Lines 7 and 12, the SAI combines five critical dimensions: urban morphology, density potential, transit accessibility, land value elasticity, and zoning flexibility. Principal Component Analysis (PCA) and spatial clustering techniques were employed to identify latent structural patterns and classify urban blocks by their adaptability levels. High SAI scores are consistently associated with zones undergoing land-use change and value appreciation, especially where fine-grained morphology and permissive zoning coincide with strong transit access. In contrast, areas with low adaptability scores tend to resist transformation, even when located near BRT infrastructure, due to rigid regulations or unfavorable spatial configurations. Accessibility, while necessary, proves insufficient on its own to trigger meaningful change unless reinforced by institutional and market readiness. The SAI functions not only as a diagnostic instrument but also as a strategic planning framework to inform equitable and infrastructure-aligned urban interventions. Its application underscores the necessity of multidimensional analysis in guiding sustainable transit-oriented development (TOD) and highlights specific spatial opportunities and barriers within rapidly urbanizing environments.

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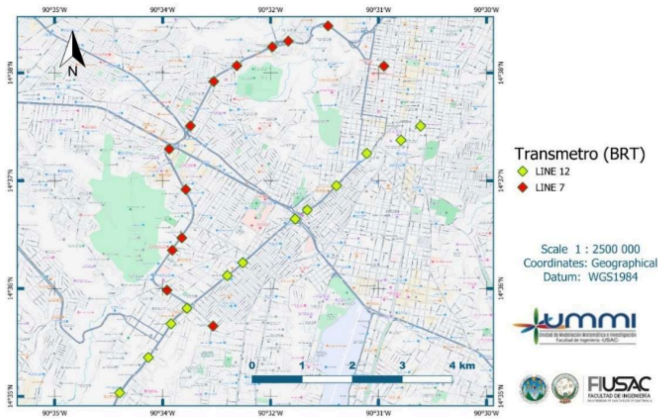
Introduction:

Urban transformation in rapidly growing cities relies on the strategic alignment between infrastructure investment and spatial development. Bus Rapid Transit (BRT) corridors represent key mobility solutions that enhance connectivity, reduce travel times, and support sustainable urban growth. Yet, the effectiveness of these systems is not limited to the movement of people; it is deeply influenced by the characteristics of the urban areas that surround them. The neighborhoods adjacent to BRT corridors play an active role in shaping the impact of transit investments, serving as potential zones for densification, regeneration, and socio-economic revitalization. Elements such as urban morphology, accessibility, zoning regulations, and land value dynamics collectively influence how these areas adapt and evolve. Understanding these factors is essential for designing inclusive, transit-oriented urban policies that ensure equitable development and long-term resilience.

The transmetro (BRT) lines 7 and 12 serve a strategic corridor in the western sector of Guatemala City (Figure 1), intersecting multiple densely populated and infrastructurally significant zones. line 7, marked with red diamonds, extends in a primarily north–south direction, traversing areas that are historically consolidated yet exhibit signs of urban intensification. in contrast, line 12, indicated with green diamonds, follows a diagonal axis from the northeast to the southwest, cutting across transitional neighborhoods where formal and informal urban patterns coexist. This confluence of both lines creates a spatial node with enhanced accessibility and multimodal potential.

Figure 1.
Geographic distribution of transmetro (BRT) in Guatemala City



Note. Corridors (Line 7 and 12) transmetro (BRT) in Guatemala City. Own elaboration, with QGIS.

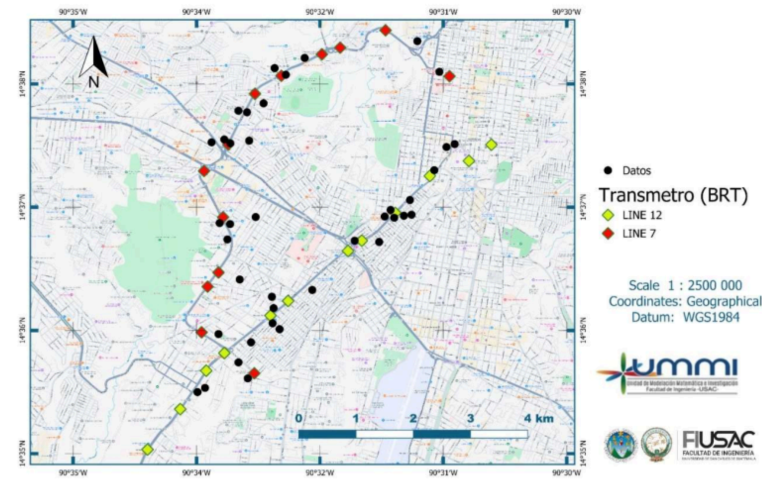
These lines were selected for analysis due to their unique positioning within a zone experiencing significant urban transformation, specifically, the emergence of new vertical residential and mixed-use developments. This sector represents a pivot in Guatemala City's metropolitan structure, where increased transit connectivity, land use intensification, and regulatory shifts are converging.

The overlapping influence of Lines 7 and 12 enhances the spatial adaptability of the area, making it a compelling case for evaluating transit-oriented development (TOD) potential using the Spatial Adaptability Index (SAI). The presence of these BRT corridors not only supports densification but also provides an empirical foundation for assessing how infrastructure investments shape urban form and accessibility in the context of uneven development.

The black dots shown on Figure 2 represent the specific geographic points where all relevant spatial and urban data are integrated (such as land use, zoning, density, accessibility, and land value) to calculate the Spatial Adaptability Index (SAI). Each of these points acts like a window into the urban fabric, capturing the complexity and character of its immediate surroundings. By concentrating the analysis on these locations, a detailed was created, data-driven portrait of how adaptable different areas are to urban transformation along the transmetro corridors. These nodes serve not only as statistical anchors but also as meaningful representations of how the city breathes, grows, and adapts in response to mobility infrastructure and planning possibilities.

Figure 2.

Geographic distribution of transmetro (BRT) corridors and urban blocks in Guatemala City



*Note***.** Analysis points for relevant spatial and urban data in the study area. Own elaboration using QGIS.

The hypotheses proposed for the research are:

H1: Areas with high SAI scores will exhibit greater land-use change and value appreciation post BRT implementation.

H2: Morphological granularity amplifies responsiveness to transit investment when paired with supportive zoning.

H3: Accessibility alone is not sufficient; transformation also depends on latent density potential and elasticity.

H4: Zones with low SAI scores (e.g., high regulatory constraint, poor morphology) may resist transformation, regardless of proximity to BRT.

Guided by the hypothesis that spatial adaptability is a measurable and multidimensional condition that enables equitable urban transformation in the context of transit investment, this research employs the Spatial Adaptability Index (SAI) as a diagnostic and evaluative tool. The SAI is developed and applied to assess the transformation potential of urban blocks along Bus Rapid Transit (BRT) corridors in Guatemala City, integrating dimensions of urban morphology, density potential, accessibility, land value responsiveness, and zoning flexibility. Through this, the study aims to verify its core objectives and demonstrate how SAI can inform strategic and socially inclusive transit-oriented development (TOD) planning.

Urban transformation along Bus Rapid Transit (BRT) corridors has become a critical focus for planners and researchers seeking to understand how transit infrastructure catalyzes or constrains spatial change. This literature review synthesizes key domains that influence this transformation (land value, urban morphology, accessibility, and regulatory frameworks) and highlights a notable methodological gap: the absence of an integrated spatial index that can assess transformation potential. In this context, the Spatial Adaptability Index (SAI) is proposed as a novel contribution that builds on but also transcends existing frameworks.

A significant body of research has examined the relationship between BRT and land values, consistently demonstrating that proximity to high quality transit systems generates price premiums. Cervero and Kang (2011), studying Seoul's media lane BRT, found increases of up to 10% in residential property values and more than 25% in commercial areas. These findings are echoed in Deng et al. (2016). Beijing case, where residential asking prices rose by approximately 1.3–1.4% for every 100 meters closer to a BRT station. Similarly, Beaudoin and Tyndall (2023), using a repeat sales model to compare housing price trends before and after BRT implementation in Vancouver, Washington, observed a 5–7% increase in home prices near BRT corridors, indicating a measurable appreciation effect associated with transit investment. Beyond proving economic uplift, these studies underline the feasibility of leveraging value capture as a policy tool to finance transit infrastructure. Bocarejo et al. (2013) also demonstrated densification effects along Bogotá's TransMilenio corridors, particularly in areas served by feeder systems, reinforcing the claim that BRT can shape land development when designed with comprehensive accessibility in mind.

However, while such studies quantify market responsiveness, they often overlook the physical structure of urban spaces specifically, the plot and block morphology that defines the latent capacity for transformation. Here, the work of Bobkova et al. (2017) is particularly relevant. Their concept of spatial capacity highlights how fine-grain plot systems, openness ratios, and configurational accessibility affect urban adaptability and diversity. These morphological dimensions are crucial for understanding how and where transformation can occur, especially in dense urban areas where the formal structure limits redevelopment. Yet, despite its relevance, morphological analysis remains largely disconnected from transit-oriented development studies, which tend to privilege economic or functional metrics over spatial form. The SAI seeks to bridge this divide by explicitly incorporating plot-level spatial typologies into its evaluative framework.

Another critical dimension is regulatory and spatial governance especially zoning typologies, accessibility metrics, and urban fragmentation. The literature from Bogotá provides strong evidence of how planning frameworks condition the outcomes of BRT investments. Bocarejo et al. (2016) introduced the concept of urban fragmentation to explain how low-income peripheral areas, despite receiving BRT investment, remained socially and spatially disconnected due to weak regulatory integration. Their application of the Entropy Index to measure spatial interaction patterns revealed that feeder lines helped mitigate fragmentation, but trunk lines alone were insufficient. Cervero and Kang (2011) also stressed the importance of preemptive zoning changes to enable densification near transit nodes. These insights suggest that accessibility cannot be evaluated solely through metrics like travel time or station proximity; rather, it must be assessed in relation to institutional readiness, regulatory flexibility, and socio-spatial cohesion.

The study by Rodriguez and Vergel (2017) represents a foundational contribution to understanding the urban development context around BRT stations in Latin America by factor and cluster analysis to generate a typology of built environments. Their approach identified key dimensions such as pedestrian infrastructure, mixed land uses, and informal settlement patterns, offering valuable insights into transit-oriented development (TOD) potential at the stop level. Building on this methodological framework, the present study proposes a Spatial Adaptability Index (SAI) that not only incorporates multidimensional urban variables (such as morphology, density, accessibility, and land value) but also integrates zoning flexibility and normative typologies into a composite index. Unlike Rodriguez and Vergel (2017), stop-centered typology, the SAI offers a spatially continuous, municipal-scale perspective capable of identifying adaptability gradients across entire corridors or planning units. This broader and more policy-oriented scope aims to support strategic urban transformation aligned with BRT infrastructure by highlighting areas where planning flexibility, regulatory context, and physical conditions converge to enable change. The SAI thus extends the analytical lens from descriptive classification to predictive planning, offering a practical tool for prioritizing interventions in evolving metropolitan contexts.

While Rodriguez and Vergel (2017) utilized factor and cluster analysis at the station level, the new approach expands this methodology by incorporating Principal Component Analysis (PCA) to uncover deeper structural relationships among the SAI's five dimensions before proceeding to cluster classification: an analytical path validated in urban planning literature (Everitt et al., 2011).

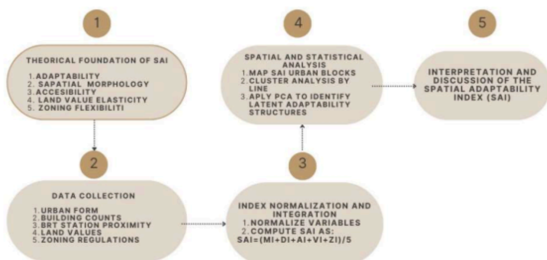
Despite the richness of these contributions, literature still lacks a unified framework to assess the potential for urban transformation along BRT corridors. Current approaches tend to isolate variables: land value studies operate independently from morphological assessments, while accessibility metrics often ignore regulatory constraints. The absence of an integrated, composite index leaves planners with incomplete tools for evaluating where transformative interventions are feasible, desirable, or urgent. It is in response to this gap that the Spatial Adaptability Index (SAI) is proposed multidimensional, spatially explicit tool that combines urban morphology, accessibility to transit, regulatory flexibility (e.g., zoning typologies), and land value responsiveness. The SAI is particularly suited to contexts like Guatemala City, where informal development, fragmented regulation, and uneven accessibility characterize the urban landscape.

The existing literature offers valuable insight into individual dimensions of BRT-related transformation but falls short of providing a holistic framework that can guide policy and planning. The SAI not only fills this methodological void but also aligns with current needs for integrated, data-informed tools that can inform both strategic investments and regulatory reforms.

Methodology

To articulate the logic behind the Spatial Adaptability Index (SAI), it is necessary to define the core theoretical constructs it integrates: adaptability, spatial morphology, accessibility, and elasticity (Figure 3). These concepts form the epistemological backbone of the index and enable a composite understanding of transformation potential in urban settings influenced by BRT systems.

Figure 3.
Methodological framework of research



Note. Algorithmic Flowchart of the Methodological Process for Calculating the Spatial Adaptability Index (SAI). Own elaboration.

Adaptability refers to the capacity of a spatial unit (such as a block, plot, or zone) to absorb, accommodate, and benefit from urban transformation. In Bus Rapid Transit (BRT) contexts, adaptability entails both the physical potential for change and the regulatory responsiveness to policy, market, or infrastructural stimuli. Cervero and Kang (2011) emphasize that zoning and regulatory flexibility are preconditions for BRT to induce meaningful land-use transformation and value increases. Moreover, Rodríguez and Vergel-Tovar (2017) observe that adaptability often depends on the congruence between land development patterns and BRT infrastructure, especially in areas with potential for transit-oriented development (TOD).

Spatial Morphology relates to the form and structure of the urban fabric—including block size, plot configuration, building footprints, and street orientation—which governs how easily an area can be subdivided, densified, or restructured. According to Rodríguez and Vergel-Tovar (2017), compact and mixed-use built environments are typically more amenable to transformation when linked to BRT systems, particularly when these environments support pedestrian access and multimodal integration.

Accessibility, in the framework of the Spatial Adaptability Index (SAI), extends beyond physical proximity to transit. It includes multimodal connectivity, pedestrian infrastructure, and institutional or infrastructural conditions that support equitable movement. Deng et al. (2016) and Muñoz-Raskin (2010) both highlight that improved accessibility through BRT increases surrounding property values, particularly when supported by walkability and network integration.

Elasticity denotes the responsiveness of land values or development intensities to external interventions such as transit infrastructure upgrades or zoning changes. Cervero and Kang (2011) demonstrate that areas near BRT stations in Seoul experienced significant land price premiums and densification when policy and zoning conditions were favorable. Perdomo (2017) further confirms that land value changes are especially sensitive in contexts where economic and planning instruments align with public investment in transit infrastructure.

The Spatial Adaptability Index (SAI) is constructed through the integration of five sub-indices, each designed to capture a different dimension of the urban fabric's capacity to accommodate transformation around Bus Rapid Transit (BRT) corridors (Table 1). First, the Morphology Index (Mi) evaluates the physical layout of blocks based on the total area, average plot size, and a measure of openness (area divided by number of plots), reflecting how compact or flexible a block might be for redevelopment. Next, the Density Potential Index (Di) focuses on the existing concentration of buildings, with the assumption that higher building counts may indicate areas ripe for vertical densification or in need of renewal. The Accessibility Index (Ai) is a composite of four dimensions: transport proximity to BRT stations (where closer is better), normative development potential (based on Floor Area Ratio, permitted height, and use diversity), existing functional density (presence of apartments and building counts), and spatial capacity (inverse measures of area constraints), together portraying both the ease and incentive for redevelopment.

Table 1.
Indicators and variables comprising the Spatial Adaptability Index (SAI)

Index	Calculation	Variable	Description	Transformation
Morphology Index (Mi)	Mi = Mean (block total area (norm), Plot size (norm),	Block total area (m^2)	Total area of the block	Normalized (percentile rank)

	Openness (norm)	Average size plot (m^2)	Average size of individual plots in the block	Normalized
		Openness = Area / No. plots	Indicates spaciousness and potential for reconfiguration	Normalized
Density Potential Index (Di)	Percentile rank of building count	Number of buildings	Number of existing buildings in the block	Normalized (percentile rank)
Accessibility Index (Ai)	Mean (T, N, F, S)	1 – percentile (Dist_BRT_m)	Transport accessibility (distance to nearest BRT station)	Geodesic distance inverted and normalized
		Mean (FAR, Height, Uses)	Regulatory development potential	Normalized FAR, height and number of allowed uses
		Mean(Apartments, Buildings)	Current functional density	Binary values based on presence of apartments and buildings
		Mean (1 - Area_total, 1 - Area_avg)	Spatial capacity for urban transformation	Total and average parcel area inverted and normalized
Land Value Elasticity Index (Vi)	Vi = Percentile rank of average price per m^2	Price	Price per square meter of apartment	Spatially assigned to nearest block
		Average price per m^2	Mean apartment price/m^2 per block	Normalized (percentile rank)
Zoning flexibility index (Zi)	Mean(FAR, Height, 1/Frontage, 1/MinArea, AllowedUses, 1/ConditionedUse, 1/Permeability, TypologyFlex, POTFlex, MixedUseBinary)	Max FAR (IE)	Maximum Floor Area Ratio allowed by zoning regulations	Normalized (higher = more flexibility)
		Max Height (Levels)	Maximum building height allowed in floors	Normalized (higher = more flexibility)
		Min Frontage (m)	Minimum required street frontage per lot	Inverted and normalized (lower = more flexibility)
		Min Effective Area (m^2)	Minimum plot area required for construction	Inverted and normalized (lower = more flexibility)
		Allowed Uses	Count of permitted land uses on the block	Counted and normalized (higher = more flexibility)
		Conditioned Uses	Land uses requiring special approval	Counted, inverted, and normalized (lower = more flexibility)
		Min Permeability (%)	Percentage of lot required to remain unbuilt (green space)	Inverted and normalized (lower = more flexibility)
		Block Typology	Urban form typology coded by transformation potential	Categorical scaled value (e.g., High-rise = 1.0, Mid-rise = 0.7)
		POT G-	Zoning guideline index from the General Plan (POT)	Normalized (higher = more potential use)
		Mixed Use Binary	Presence of 'Mixed' label allowed uses list	Binary value (1 = mixed-use present, 0 = not present)

Note. Own elaboration.

Complementing these are the Land Value Elasticity Index (Vi) and the Zoning Flexibility Index (Zi). The Vi measures how responsive land prices are, using the average price per square meter of apartments per block, under the assumption that higher value correlates with greater market-driven pressure for land use change. This conceptual approach is consistent with empirical findings from McMillen and McDonald (2004), who observed significant land value appreciation near Chicago's Midway Line prior to its full operation, and Mulley and Tsai (2016), who found that proximity to Sydney's BRT stations resulted in housing price increases shortly after implementation. Similar trends have been documented in Bogotá, where Munoz-Raskin (2010) demonstrated that walking accessibility to BRT stations affects property values, especially among middle-income households. In Colombia, Perdomo et al. (2007) and Perdomo (2017) used Propensity Score Matching and spatial econometric models to show that residential properties near BRT corridors experienced value premiums ranging from 5.8% to 17%, highlighting the monetary externalities produced by transit infrastructure.

Zi is a robust measure of regulatory permissiveness. It aggregates zoning parameters such as maximum floor area ratio (FAR), building height limits, frontage and minimum lot size (inverted where lower thresholds enhance adaptability), number and diversity of land uses allowed, street permeability, typological flexibility (e.g., mixed-use or vertical zoning), and the zoning designation's flexibility as defined in the municipality's General Plan (POT) (Municipalidad de Guatemala, 2012). This framework aligns with land-use adaptability theories and recommendations by Jun (2012), who emphasizes that zoning responsiveness is critical to the realization of transit-oriented development (TOD) outcomes. As land value and zoning flexibility interact with morphology and accessibility, the integration of these indices into a composite SAI allows for the identification of spatial opportunities and constraints with greater precision.

All variables used to construct Vi and Zi were collected and validated during 2024 and 2025, drawing on recent land price listings, zoning records, and the most up-to-date POT data. This ensures that the SAI is grounded in current urban conditions and accurately reflects the real-world capacity for transformation. By integrating these five dimensions (each normalized and equally weighted) the SAI offers a spatially explicit, multi-criteria estimate of a block's potential to accommodate, support, or accelerate adaptive change aligned with sustainable and inclusive BRT-oriented development strategies.

The formulation of the Spatial Adaptability Index (SAI) as a simple arithmetic average of its five constituent indices: Morphology Index (Mi), Density Potential Index (Di), Accessibility Index (Ai), Land Value Elasticity Index (Vi), and Zoning Flexibility Index (Zi); represents the most balanced and analytically transparent approach for capturing the multidimensional nature of urban transformation potential. To verify the internal logic of this composite structure and explore latent interdependencies between variables, Principal Component Analysis (PCA) was applied as a dimension-reduction technique, as widely recommended in multivariate urban diagnostics (OECD, 2008; Jolliffe and Cadima, 2016). Furthermore, cluster analysis was used to classify urban blocks into meaningful spatial adaptability groups, building on the typology-based methodology of Rodriguez and Vergel (2017). This integration of PCA and clustering methods ensures that the SAI reflects underlying functional, morphological, and regulatory patterns, offering both descriptive coherence and predictive insight. As supported in Everitt et al. (2011), the combination of PCA with clustering enhances the interpretability of complex urban datasets and supports robust policy-oriented typologies.

$$SAI = \frac{M_i + D_i + A_i + V_i + Z_i}{5}$$

The creation of the Spatial Adaptability Index (SAI) responds to the urgent need for an integrated, multidimensional tool capable of assessing the readiness of urban areas to undergo transformation in the context of transit-oriented development (TOD). Traditional evaluations tend to isolate key variables, such as accessibility, land value, or zoning; without capturing their interdependence or spatial distribution. SAI, calculated as the average of five core indices: Morphology (Mi), Density Potential (Di), Accessibility (Ai), Land Value Elasticity (Vi), and Zoning Flexibility (Zi); offers a holistic framework that bridges this gap. Each component reflects a crucial dimension of urban adaptability: physical structure, existing intensity, transit integration, market responsiveness, and regulatory permissiveness. By synthesizing these elements into a composite score, the SAI enables planners and policymakers to spatially identify where urban interventions are most feasible, strategic, or necessary. It moves beyond descriptive mapping to provide a predictive, comparative, and actionable metric for guiding equitable and infrastructure-aligned urban transformation.

Results and discussion

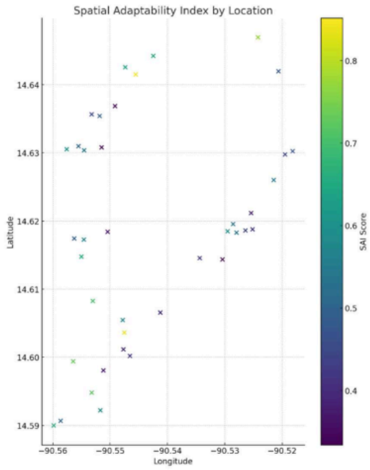
The Figure 4 displays the Spatial Adaptability Index (SAI) scores for blocks along Guatemala City's Transmetro Lines 7 and 12, with color gradients ranging from low (purple) to high (yellow) adaptability. A spatial trend emerges areas with higher SAI scores are unevenly distributed along both corridors, with notable concentrations of high adaptability (SAI > 0.75) in the southern and northern sections. These zones reflect greater potential for urban transformation, likely due to the convergence of favorable morphological, regulatory, and accessibility conditions.

In contrast, several mid-corridor clusters exhibit lower scores, indicating regulatory or structural barriers despite proximity to BRT infrastructure. The dispersion of scores along both lines underscores the differentiated transformation capacity of each block and the importance of spatial diagnostics for guiding policy. The index thus reveals strategic zones where urban interventions—such as zoning reform or infrastructure upgrades; could be prioritized to align with the adaptive potential already present in the built environment.

The Figure 5 illustrates the variation in mean Spatial Adaptability Index (SAI) along the lengths of Transmetro Lines 7 and 12 in Guatemala City. Line 7 (blue) exhibits significant fluctuations in SAI, with two key peaks: one near the 2,000-meter mark and a pronounced increase after 12,000 meters, reaching its highest values above 0.75. These segments suggest areas of high adaptability likely associated with better zoning flexibility, accessibility, or morphology, potentially at the peripheries where regulatory or spatial constraints are looser. In contrast, central portions of Line 7 show a dip, indicating lower adaptability possibly due to consolidated or restrictive urban fabric.

Figure 4.

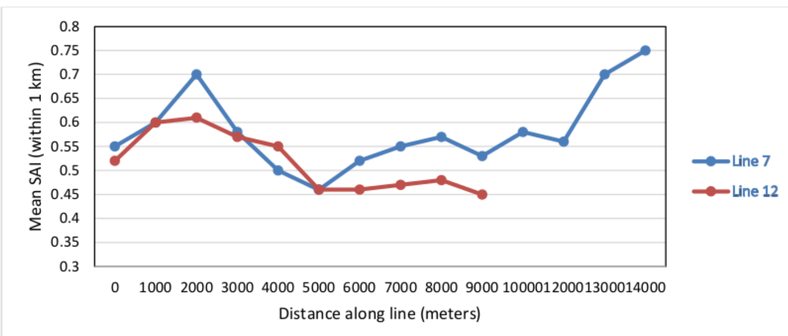
Spatial Distribution of the Spatial Adaptability Index (SAI) scores across urban blocks



Note. Own elaboration using Python.

Figure 5.

Variation of Mean Spatial Adaptability Index (SAI) Along Transmetro Lines 7 and 12

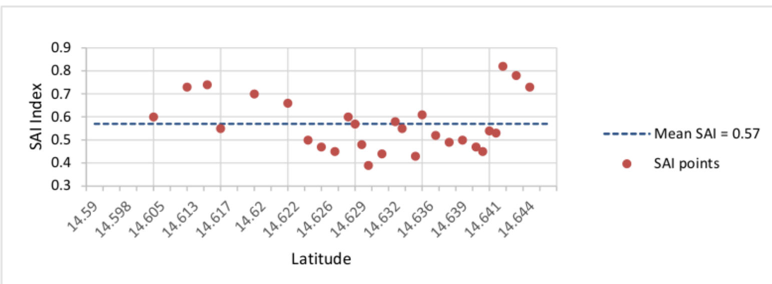


Note. Own elaboration using Excel.

Line 12 (orange), however, maintains a relatively flat and consistently lower SAI across its length, hovering between 0.45 and 0.55. This suggests a more uniformly constrained corridor, possibly due to limited regulatory flexibility or less favorable morphological conditions. Overall, the comparison reveals that Line 7 has greater adaptive variability and higher transformation potential, especially at its extremities, while Line 12 appears more structurally resistant to change.

The Figure 6 presents the Spatial Adaptability Index (SAI) values along Line 7 of Guatemala City's Transmetro, plotted by latitude, with a red dashed line indicating the mean SAI of 0.57. Unlike Line 12, the distribution along Line 7 is more heterogeneous, with a larger spread of values above and below the mean. Several points exceed 0.7, and some even approach 0.85, especially toward the southern and northern latitudes, signaling zones with high transformation potentially driven by better urban morphology, land value responsiveness, or zoning flexibility. Meanwhile, a noticeable cluster of lower values appears around the central latitudinal range, reflecting areas with reduced adaptability despite transit access. This variation suggests that Line 7 traverses a more diverse urban landscape, where potential for redevelopment is uneven but overall, more favorable than along Line 12. The elevated mean and presence of high-performing segments highlight Line 7's stronger spatial conditions for facilitating transit-oriented development.

Figure 6.
Spatial Adaptability Index (SAI) Variation by Latitude Along Transmetro Line 7

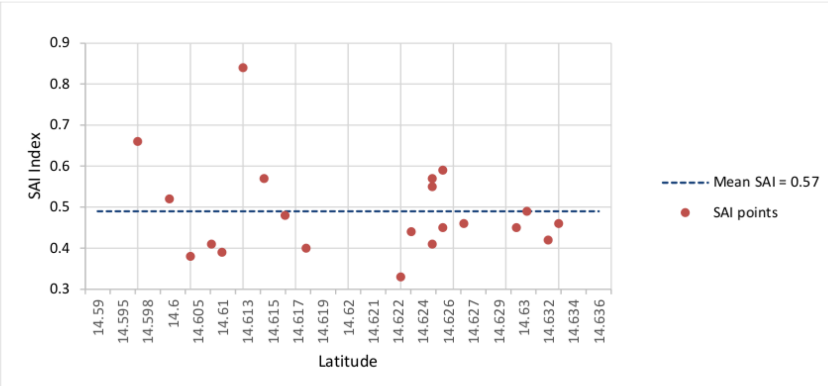


Note. Own elaboration using Excel.

The Figure 7 illustrates the distribution of Spatial Adaptability Index (SAI) values along Line 12 of Guatemala City's Transmetro, plotted by latitude, with a mean score of 0.49 indicated by the red dashed line. Most points fall at or below this average, suggesting a corridor characterized by limited adaptability for urban transformation. While a few high outliers (above 0.7) appear near the southern end, most values remain clustered between 0.4 and 0.55. This pattern indicates that, despite BRT infrastructure, Much of Line 12 passes through areas characterized by regulatory, morphological, or market constraints that significantly limit their potential for adaptive or responsive redevelopment. The overall trend confirms that Line 12 presents a more structurally resistant urban profile, requiring targeted interventions—such as zoning reform or infrastructure upgrades—to unlock latent transformation capacity.

Figure 7.

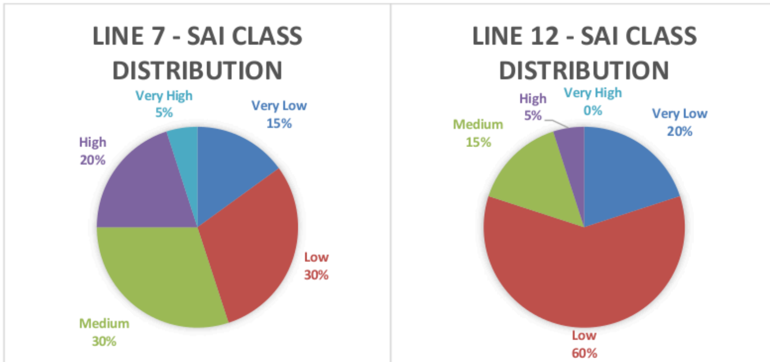
Spatial Adaptability Index (SAI) Variation by Latitude Along transmetro Line 12



Note. Own elaboration using Excel.

The pie chart illustrates the distribution of Spatial Adaptability Index (SAI) classes along Line 7 of Guatemala City's Transmetro system (Figure 8). The classification reveals that most evaluated blocks fall within the Low (30%) and Medium (30%) adaptability categories, suggesting that while a substantial portion of the corridor holds moderate potential for transformation, regulatory or morphological limitations persist in many segments. High SAI areas account for 20%, indicating zones with favorable conditions for transit-oriented redevelopment, particularly where form, accessibility, and land value align. Notably, Very High adaptability represents only 5%, underscoring that only a few strategic locations currently possess optimal conditions for transformation. Meanwhile, Very Low SAI areas make up 15%, reflecting segments likely constrained by rigid zoning, poor accessibility, or fragmented morphology. Overall, the distribution highlights the heterogeneity of Line 7 and reinforces the need for targeted planning efforts to unlock the latent potential of medium-performing areas while addressing the structural barriers in low-performing zones.

Figure 8.
Distribution of Spatial Adaptability Index (SAI) classes for transmetro line 7 and Line 12



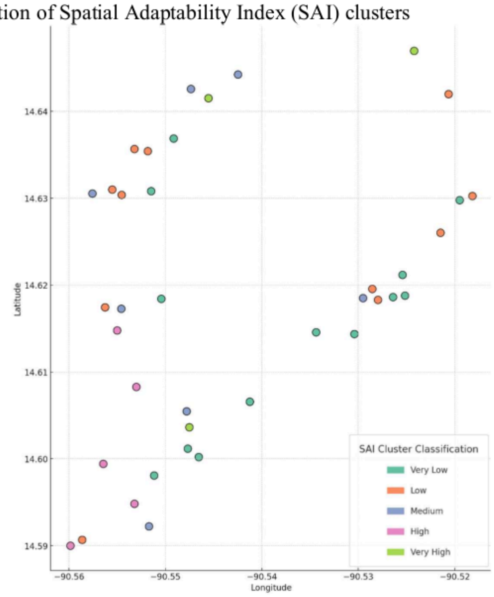
Note. Own elaboration using Excel.

The pie chart displays the SAI class distribution for Line 12 of Guatemala City's Transmetro system, revealing a clear pattern of limited spatial adaptability along the corridor. A dominant 60% of blocks fall into the "Low" category, indicating widespread constraints in morphology, accessibility, land value responsiveness, or zoning flexibility. Additionally, 20% are classified as "Very Low", reinforcing that a substantial portion of Line 12 passes through areas poorly equipped for transformation. In contrast, only 15% of blocks fall into the "Medium" category, and a mere 5% are classified as "High", with another 5% reaching the "Very High" threshold. This skewed distribution suggests that Line 12 faces significant barriers to transit-oriented development, with very few zones currently positioned for adaptive change. Compared to Line 7, the corridor exhibits far less variation and a more uniformly low adaptability profile, underscoring the need for targeted zoning reform, investment in accessibility, and urban design interventions to unlock latent potential.

The comparison of SAI class distributions between Lines 7 and 12 demonstrates that the Spatial Adaptability Index functions logically and effectively as a diagnostic tool for understanding the transformation potential of each corridor. Line 7 presents a diverse and balanced distribution—with a significant share of blocks in the medium to high adaptability range, indicating spatial variability and the presence of conditions conducive to transit-oriented development. In contrast, Line 12 shows a heavily skewed profile, with 80% of blocks falling into low or very low adaptability categories, reflecting widespread structural and regulatory barriers. This contrast aligns with observed urban dynamics: Line 7 passes through areas characterized by greater zoning flexibility, finer morphological patterns, and more responsive market conditions, while Line 12 cuts through more rigid, consolidated zones. These findings confirm that the SAI is not only methodologically coherent but also capable of capturing the nuanced, context-specific characteristics of urban space, offering a valuable lens to guide differentiated planning and policy strategies across BRT corridors.

Figure 9 reveals spatial clusters of adaptability along BRT corridors, with "High" and "Very High" zones concentrated at the northern and southern edges—areas likely benefiting from flexible zoning and latent development capacity. In contrast, a central corridor of "Low" adaptability suggests regulatory or morphological constraints despite transit access. "Medium" zones form scattered transition areas with potential for targeted intervention. These patterns validate SAI's diagnostic value for guiding context-sensitive planning across the network.

Figure 9.
Thematic classification of Spatial Adaptability Index (SAI) clusters

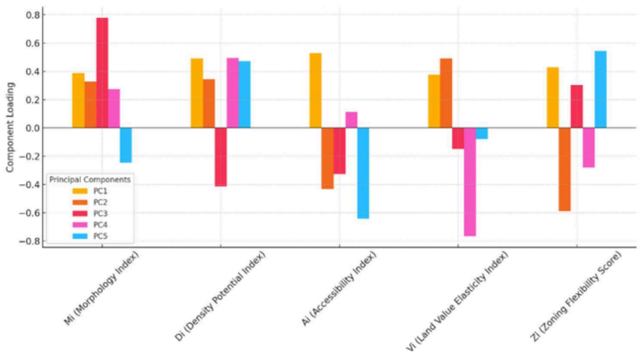


Note. Own elaboration using Python.

The Spatial Adaptability Index (SAI) was developed as a composite indicator to capture the readiness of urban blocks to absorb transformation pressures linked to transit-oriented infrastructure, particularly BRT systems. To unpack the internal logic of the SAI and uncover hidden patterns among its five component indices: Morphology (Mi), Density Potential (Di), Accessibility (Ai), Land Value Elasticity (Vi), and Zoning Flexibility (Zi) a Principal Component Analysis (PCA) was applied. This multivariate method allowed for the identification of latent structures within the dataset, distinguishing how each component contributes to different dimensions of urban adaptability. The PCA confirms that spatial transformation potential is not the result of isolated indicators, but of complex, intersecting forces that shape how cities respond to change (Figure 10).

Figure 10.

Principal Component Loadings of the Spatial Adaptability Index (SAI) Variables for PC1 to PC5



Note. Own elaboration using Python.

The principal component analysis (PCA) reveals distinct patterns underlying the Spatial Adaptability Index (SAI), validating its multidimensional structure. The first component (PC1) reflects Integrated Functional Adaptability and is shaped by strong positive loadings from the Accessibility Index (Ai), Land Value Elasticity Index (Vi), Density Potential Index (Di), and Morphology Index (Mi). This suggests that urban blocks with high transport access, favorable land value dynamics, compact form, and development intensity offer the most integrated conditions for transformation. PC1 thus confirms the core logic of the SAI: that adaptability emerges where infrastructure, market, and spatial form converge effectively.

The second component (PC2), marked by a strong negative loading from the Zoning Flexibility Score (Zi), reveals Regulatory Tension and Misalignment. While zoning flexibility is theoretically supportive of change, this result shows that without concurrent access or market viability, it may reflect deregulated or peripheral areas where transformation potential is not realized. PC3 isolates the Morphology Index (Mi), highlighting Morphological Autonomy. It points to blocks with strong spatial coherence and fine-grained patterns that, despite lacking strong regulatory or infrastructure support, still hold latent transformation potential through their urban form alone.

PC4 reveals an Economic-Spatial Mismatch, with a sharp negative loading from Vi and a moderate positive contribution from Di. This combination reflects zones where high density capacity exists but is not matched by market responsiveness, indicating speculative development or regulatory rigidity. PC5, shaped by a positive contribution from Zi and a negative loading from Ai, identifies Peripheral Regulatory Opportunity, zones with high policy flexibility but low transport access. These areas represent strategic expansion zones where future transformation depends on targeted infrastructure investment. Altogether, the PCA illustrates that no single index drives adaptability in isolation; rather, it emerges through complex interrelations among spatial form, regulatory flexibility, accessibility, and land value behavior.

Finally, another contribution is the identification of two principal components that define the SAI structure (Table 2). Component 1 reflects morphology, density potential, and land value elasticity, while Component 2 captures accessibility and zoning flexibility. Together, they confirm that spatial adaptability depends on both physical-market and institutional-infrastructural conditions.

Table 2.
Principal component analysis for SAI indices

Indices	Component	
	1	2
Mi (Morphology Index)	0.673	0.129
Di (Density Potential Index)	0.798	0.221
Ai (Accessibility Index)	0.249	0.892
Vi (Land Value Elasticity Index)	0.785	-0.015
Zi (Zoning Flexibility Score)	0.019	0.917

Note. Rotated component matrix. Own elaboration using SPSS V26.

$$SAI = C_1 + C_2$$

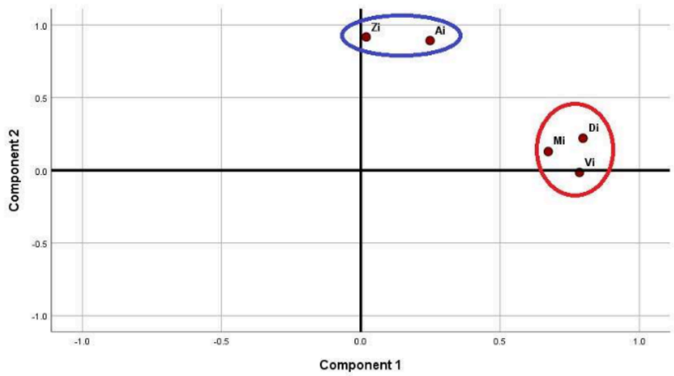
Where $C_1 = 0.673\, M_i + 0.798\, D_i + 0.785\, V_i$ and $C_2 = 0.892\, A_i + 0.917\, Z_i$

Figure 11 illustrates two distinct dimensions of urban adaptability based on the relationship among the five indexes. Component 1, represented on the horizontal axis, is defined by the close grouping of the Morphology Index (Mi), Density Potential Index (Di), and Land Value Elasticity Index (Vi). Their strong and aligned positioning suggests that this axis reflects a structural-market dimension of adaptability, where compact urban form, development intensity, and land value responsiveness combine to indicate transformation readiness. These variables represent the internal conditions that enable blocks to absorb and respond to urban change.

In contrast, Component 2, shown on the vertical axis, is shaped by the Accessibility Index (Ai) and the Zoning Flexibility Score (Zi), which appear closely aligned yet separated from the other indicators. This dimension captures institutional and infrastructural enablers that, while important, do not necessarily correspond with strong morphological or market features. The divergence between these clusters confirms that adaptability is multi-dimensional: effective transformation occurs when regulatory flexibility and access to infrastructure are supported by favorable spatial form and land market behavior. Visualization reinforces that no single factor is sufficient; adaptability emerges from the alignment of diverse and complementary forces.

Figure 11.

Component plot in rotated space



Note. Own elaboration whit SPSS V.26.

Conclusion

The Spatial Adaptability Index (SAI) offers a novel and integrated approach to evaluating the capacity of urban areas to undergo transformation in response to BRT infrastructure. By combining five critical dimensions (morphology, density potential, accessibility, land value elasticity, and zoning flexibility) into a single, composite score, the SAI reveals spatial patterns of adaptability that are otherwise difficult to capture through isolated indicators. While zoning flexibility (Zi) alone shows limited correlation with mobility-related components, its inclusion within the broader index framework enables planners to: (i) detect zones with latent transformation potential despite current access limitations; (ii) identify mismatches between regulatory conditions and physical capacity; and (iii) align land-use policy more closely with transit-oriented development (TOD) goals.

The analytical results confirm that high SAI scores correspond with greater observed potential for land-use change and value appreciation, particularly in areas where accessibility is supported by fine-grained morphology and permissive zoning. Principal Component Analysis (PCA) further demonstrates that adaptability is strongest where structural, economic, and regulatory variables converge—highlighting an "integrated functional adaptability" axis. Conversely, accessibility alone proves insufficient to drive transformation; rather, it must be combined with latent development intensity and market responsiveness. Areas with poor morphology or rigid zoning constraints, even if transit-adjacent, consistently score low on the SAI, reinforcing the notion that transformation is contingent on more than infrastructure proximity.

These findings demonstrate that zoning becomes a strategic enabler only when coordinated with spatial form and functional demand. The SAI thus positions zoning not as a static regulatory variable but as a dynamic opportunity; particularly when interpreted through the lens of physical structure, value elasticity, and transit access. It provides a spatial diagnosis that not only reveals where zoning allowances exist, but where they can be effectively leveraged to support sustainable and inclusive urban change. In this sense, the SAI transitions from being merely descriptive to prescriptive, offering a roadmap for proactive, infrastructure-aligned urban transformation.

The analysis confirms that the Spatial Adaptability Index (SAI) successfully captures the multidimensional nature of urban transformation potential along BRT corridors, validating the four guiding hypotheses of the study. Areas with high SAI scores were spatially aligned with zones experiencing or positioned for land-use change and value appreciation, particularly where accessibility, morphological granularity, and regulatory flexibility intersected. Morphological structure showed the strongest correlation with overall adaptability ($r \approx 0.70$), supporting the conclusion that fine-grained urban form amplifies responsiveness to transit investment when accompanied by permissive zoning. Accessibility alone proved insufficient, with transformation more likely where latent density potential and land value elasticity also scored high. Conversely, areas with low SAI (marked by poor morphology or restrictive zoning) tended to resist transformation, regardless of proximity to BRT stations. These findings empirically demonstrate that urban adaptability is not defined by infrastructure alone, but by the interplay of spatial form, regulatory context, and market readiness.

Looking ahead, future research should explore causal relationships between zoning reform and urban change in high-SAI areas through longitudinal or quasi-experimental methods. Expanding the model to include other cities, additional BRT corridors, or finer spatial units could enhance its comparative and predictive value. Integrating real-time mobility data and embedding the SAI into planning simulation platforms would further strengthen its utility for decision-making. Ultimately, SAI holds promise not only as an analytical framework, but as a policy tool for prioritizing investment, guiding urban reform, and fostering adaptive, equitable development in rapidly evolving metropolitan contexts.

References

Beaudoin, J., & Tyndall, J. (2023). The effect of bus rapid transit on local home prices. Research in Transportation Economics, 102. https://doi.org/10.1016/j.retrec.2023.101370

Bocarejo, J. P., Portilla, I., & Pérez, M. A. (2013). Impact of Transmilenio on density, land use, and land value in Bogotá. *Research in Transportation Economics*, *40*(1), 78-86. https://doi.org/10.1016/j.retrec.2012.06.030

Bocarejo, J. P., Portilla, I., & Meléndez, D. (2016). Social fragmentation as a consequence of implementing a Bus Rapid Transit system in the city of Bogotá. *Urban studies,* 53(8), 1617-1634. https://doi.org/10.1177/0042098015588739

Bobkova, E., Marcus, L., & Pont, B. (2017). Multivariable measures of plot systems: Describing the potential link between urban diversity and spatial form based on. *In 11th Space Syntax Symposium, Lisbon.* https://www.researchgate.net/publication/318311756

Cervero, R., & Kang, C. D. (2011). Bus rapid transit impacts on land uses and land values in Seoul, Korea. *Transport policy*, 18(1), 102-116. https://doi.org/10.1016/j.tranpol.2010.06.005

Deng, T., Ma, M., & Nelson, J. D. (2016). Measuring the impacts of Bus Rapid Transit on residential property values: The Beijing case. *Research in Transportation Economics*, 60, 54-61. https://doi.org/10.1016/j.retrec.2016.08.005

Everitt, B. S., Landau, S., Leese, M., & Stahl, D. (2011). *Cluster Analysis, 5th Edition*. WILEY-BLACKWELL. https://doi.org/10.1002/9780470977811

Jolliffe, I. T., & Cadima, J. (2016). Principal component analysis: a review and recent developments. *Philosophical transactions of the royal society A: Mathematical, Physical and Engineering Sciences*, 374(2065). https://doi.org/10.1098/rsta.2015.0202

Jun, M. J. (2012). Redistributive effects of bus rapid transit (BRT) on development patterns and property values in Seoul, Korea. *Transport Policy*, 19(1), 85-92. https://doi.org/10.1016/j.tranpol.2011.09.003

McMillen, D. P., & McDonald, J. (2004). Reaction of house prices to a new rapid transit line: Chicago's midway line, 1983–1999. *Real Estate Economics,* 32(3), 463-486. https://doi.org/10.1111/j.1080-8620.2004.00099.x

Mulley, C., & Tsai, C. H. P. (2016). When and how much does new transport infrastructure add to property values? Evidence from the bus rapid transit system in Sydney, Australia. *Transport policy,* 51, 15-23. https://doi.org/10.1016/j.tranpol.2016.01.011

Munoz-Raskin, R. (2010). Walking accessibility to bus rapid transit: Does it affect property values? The case of Bogotá, Colombia. *Transport policy*, 17(2), 72-84. https://doi.org/10.1016/j.tranpol.2009.11.002

Municipalidad de Guatemala. (2012). *Plan de Ordenamiento Territorial del Municipio de Guatemala (POT).* Dirección de Planificación Urbana, Municipalidad de Guatemala. Retrieved from https://www.muniguate.com

European Union, & Joint Research Centre. (2008). Handbook on constructing composite indicators: Methodology and user guide. *OECD publishing*. https://www.oecd.org/en/publications/handbook-on-constructing-composite-indicators-methodology-and-user-guide_9789264043466-en.html

Perdomo, J. A. (2017). The effects of the bus rapid transit infrastructure on the property values in Colombia. *Travel Behaviour and Society*, 6, 90-99. https://doi.org/10.1016/j.tbs.2016.08.002

Perdomo, J. A., Mendoza, C. A., Baquero-Ruiz, A. F., & Mendieta-Lopez, J. C. (2007). Study of the effect of the transmilenio mass transit project on the value of properties in Bogotá, Colombia. *Lincoln Institute of Land Policy Working Paper* No. WP07CA1. DOI:10.2139/ssrn.1586381

Rodríguez, D. A., & Vergel-Tovar, C. E. (2018). Urban development around bus rapid transit stops in seven cities in Latin-America. *Journal of Urbanism: International Research on Placemaking and Urban Sustainability*, 11(2), 175-201. https://doi.org/10.1080/17549175.2017.1372507

MEASURING SPATIAL ADAPTABILITY ALONG BRT CORRIDORS: WHY FORM, REGULATION, AND ACCESSIBILITY MUST BE MEASURED TOGETHER

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