A macro-scale cluster analysis of metro-based Transit-Oriented Development (TOD) patterns in Chinese and Latin American cities

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SHORT SUMMARY

Metro services shape urban built environments, but comparative macro-scale studies across developing regions remain scarce. This research evaluates 64 cities (42 Chinese, 22 Latin American) using hierarchical and k-means clustering across three scenarios: density of metro services, metro area coverage (400 m buffer), and network extensiveness per population. Four distinct city-metro interaction typologies emerge. Mega Chinese cities show high node-high place patterns (Cluster C3), while medium-sized Latin American cities exhibit intermediate node-place balance (Cluster C4) – a previously undocumented potential for pedestrian-oriented TOD. The study demonstrates that walkability proxies (400 m buffer) can be operationalized at macro scale, and that compact urban form is a necessary condition for effective TOD, even with limited metro coverage. Findings provide actionable typologies for context-specific infrastructure and pedestrian policies.

Keywords: Metro service; Built environment; Transit-oriented development (TOD); Cluster analysis.

1. INTRODUCTION

Metro services are a strategic high-capacity infrastructure that uses exclusive tracks to offer frequent, fast, and safe urban mobility (Lin et al., 2022). They shape the built environment by enhancing accessibility, guiding land use, and promoting compact urban forms. Transit-Oriented Development (TOD) represents the most advanced integration of transit and land use, aiming to create walkable, mixed-use, and dense neighborhoods around stations (Calthorpe, 1993).

Node-place to macro-scale clustering

The dominant framework for TOD evaluation is Bertolini's (1996) node-place model, which assesses station areas as both transport nodes and activity places. Subsequent micro- and meso-scale studies have generated typologies using cluster analysis. For example, Su et al. (2021) applied a node-functionality-place hierarchical clustering to five Chinese megacities, identifying balanced, stressed, and dependent station types. Lyu et al. (2016) developed a TOD typology for Beijing, revealing that many suburban stations remain "unsustained nodes". Vale et al. (2018) extended the node-place model to Lisbon's subway, showing that peripheral areas are often unbalanced. More recently, Robillard et al. (2025) proposed a methodological framework to generate TOD typologies at city level, while Cortés-Salinas et al. (2025) introduced the concept of "incomplete centrality" for Chilean metro stations.

However, all these studies focus on individual cities or single regions. No existing research has systematically compared how city-level attributes – population, density, GDP, and metro infrastructure metrics – interact across different developing regions. This gap is critical because China and Latin America represent 25 % of the world population and have contrasting metro

development trajectories: China operates the world's most extensive metro network (43 % of global infrastructure), while Latin America is the most urbanized developing region yet relies heavily on BRT (Bastidas, 2021). Without macro-scale comparative evidence, policies cannot be transferred effectively.

Research gap and contribution

This study addresses the question: What metro-based TOD patterns emerge when analyzing node-place urban attributes at macro-scale in medium, large and mega Chinese and Latin American cities? Using open data and a novel comparative design, we evaluate 64 cities (42 Chinese, 22 Latin American) that represent the totality of metro services in operation. We introduce three analytical scenarios, density of metro services, metro area coverage (400 m buffer as walkability proxy), and network extensiveness per population, to isolate different node-side dimensions. Hierarchical and k-means clustering consistently yield four distinct typologies.

2. METHODOLOGY

We selected 64 cities (31 medium, 19 large, 14 mega) based on operational metro services and open data availability (National Bureau of Statistics of China; ITDP; UITP). Seven variables were compiled: population, density, GDP per capita, density of metro services (metro km/urban km²), metro area coverage (% of urban area within 400 m of stations), network extensiveness per population (metro km/100,000 inhabitants), and daily ridership coverage.

Three scenarios were defined to isolate different node-place interactions:

- **Scenario 1:** density of metro services
- **Scenario 2:** metro area coverage (pedestrian accessibility proxy)
- **Scenario 3:** network extensiveness per population

After min-max normalization (0–1), hierarchical clustering (Ward's method) determined an optimal four-cluster solution. K-means clustering then assigned cities to typologies. The 400 m buffer follows Guerra et al. (2012) for modelling pedestrian egress.

3. RESULTS AND DISCUSSION

Four consistent clusters emerged across scenarios (Table 1 summarizes final typology):

Table 1: Variables defined to evaluate built environment interaction.

Id	Index	Description	Symbol	Equation
1	**Population**	Total residing in either an urban cluster, where the population exceeds 50,000 people	C_{PO}	C_{PO} = Urban permanent population
2	**Density**	Ratio of the population to	D	P/ C_{LA}

Id	Index	Description	Symbol	Equation
		the built-up area		
3	**Gross domestic product (GDP) per capita**	Ratio of the monetary value of final goods and services produced in a period in a year to the population	GDP_{PC}	GDP/C_{PO}
4	**Density of metro services**	Ratio of the metro length to the urban land area	L_M	$L_M = M_{KM}/C_{LA}$ (km/km^2)
5	**Network extensiveness per population**	Ratio of the network length to the urban population	L_P	$L_P = M_{KM}/C_{PO}$ (km/person*100,000)
6	**Metro area coverage**	Percentage of urban area whit in a walking distance from metro station (metro catchment area)	A	$A = M_{LA}/C_{LA\ (\%)}$
7	**Daily ridership coverage**	Ratio of ridership per day to the population	D_{RC}	$D_{RC} = R_D / C_{PO}$

Cluster C3 – High node, high place (density-based)

Only mega/large Chinese cities (e.g., Shanghai, Beijing, Chengdu). They exhibit extended metro coverage and compact land use, representing best-practice TOD.

Cluster C4 – Intermediate node, intermediate place

Mix of medium Chinese and medium Latin American cities (Caracas, Medellín, Valparaíso). Density is the most influential variable. These cities show stronger alignment between land use and transportation than larger Latin American peers – a key finding.

Cluster C2 – Low node, high/intermediate place (population-based)

Mega cities from both regions (Mexico City, São Paulo, Chongqing). High population but insufficient metro coverage leads to long commutes and reduced accessibility.

Cluster C1 – Lower/low node, intermediate place

Dominated by Latin American medium cities (58 % of cluster). Low metro density and limited pedestrian catchment.

Key contributions highlighted

Using 400 m buffer at macro scale as proxy for walkability, represent a methodological innovation, and reveals that medium Latin American cities (Cluster C4) have untapped pedestrian TOD potential, even with short metro networks, as showed in figure 1.

By regional comparison, Chinese mega cities excel in node-place synergy, but medium Latin American cities outperform larger ones in the region – contradicting the assumption that only large cities benefit from TOD.

In terms of policy-relevant typology, Cluster C4 cities (e.g., Medellín, Caracas) could prioritize pedestrian infrastructure and feeder services to leapfrog to C3-like performance without massive metro expansion, as showed in table 2.

Figure 1. Distribution and results of the 64 cities evaluated in scenario 2.

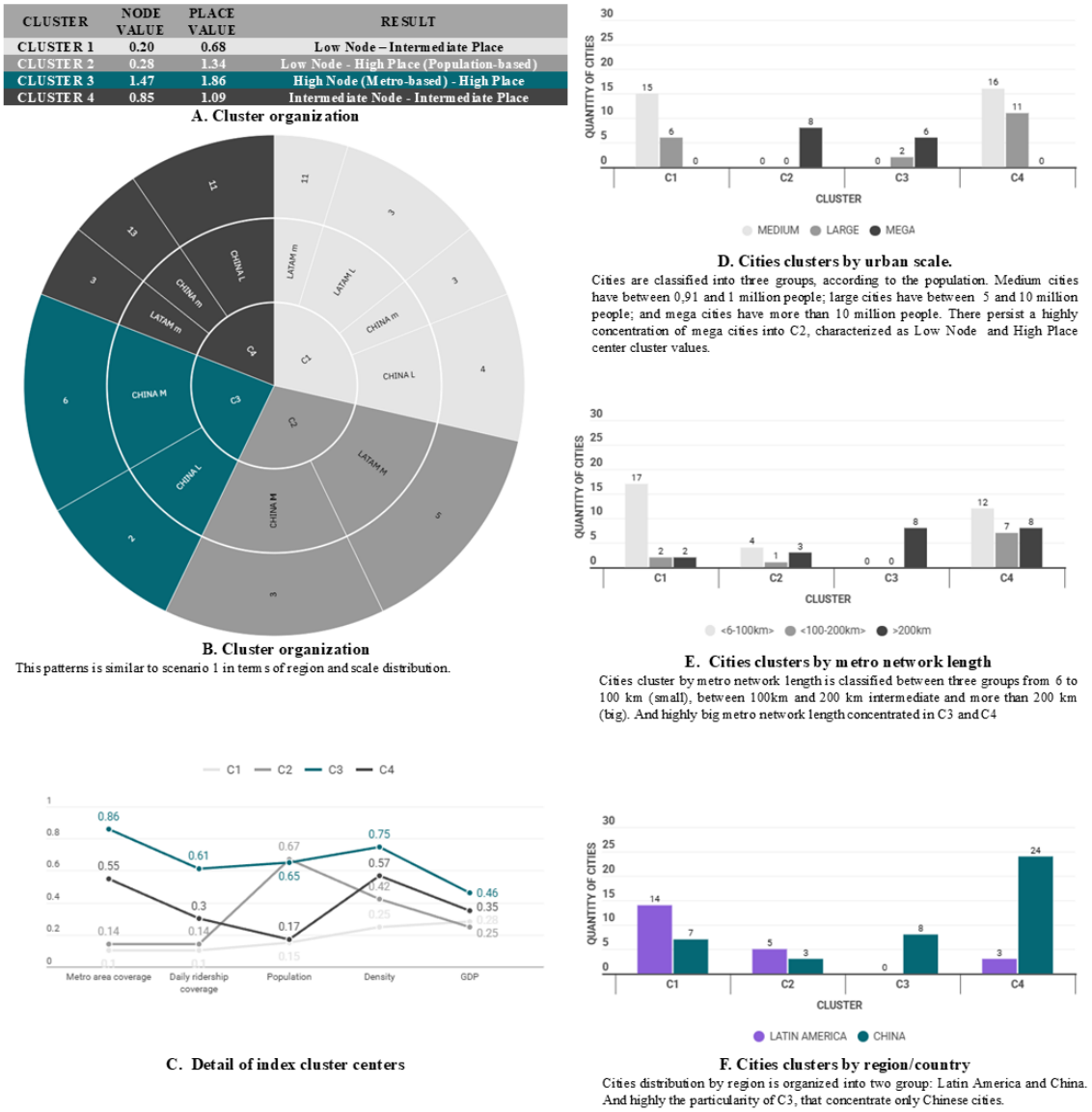


Table N° 2: Cluster comparison

Cluster	Description	Main characteristics	Patterns	Key differences
C1	Lower/Low node–intermediate place	Medium Latin American cities with small density of metro services (km).	Su et al. (2021): dependent" or "underdeveloped"; Va et al. (2021): periphery is mainly unbalance in terms of TOD.	The metro infrastructure priority with a land use integration and a metro-based pedestrian infrastructure is the priority for this kind of service, promoting polycentricity development to create dense sub-centers while carefully planning new metro lines to serve them and avoid inefficient sprawls. Transit-oriented re-zoning, and street network reconfiguration metro-based.
C2	low node–high/intermediate place (population-based)	Mega Latin American and Chinese cities small, intermediate and large density of metro services (km).	Lyu et al. (2016): "unsustained node" City size correlated to average distance (Sharifi, A., 2019) Su et al. (2021): "balanced under stress threat"	Strategic expansion of metro services to leverage the dense urban structure. Improve walking environment, promote a feeder network.
C3	high node (metro-based)–high place (density-based),	Large and mega Chinese cities with extended density of metro services (km).	Proactive integration of transportation and land-use policies (Yang et al., 2016). large city size has a correlation with lower transportation energy consumption (Sharifi, A., 2019)	Protect pedestrian space; affordable housing incentives; and placemaking, improving the level of public spaces.
C4	intermediate node–	Medium (China and Latin America) and large Chinese cities	Incomplete centrality Cortés-	Promoting pedestrian experience and integrating feeder bus

Cluster	Description	Main characteristics	Patterns	Key differences
	intermediate place	with small, intermediate and large metro services.	Salinas et al. (2025). Allow of public transportation to be organized around a variety of centers Robillard, et al. (2025)	services to maximize the existing synergy, complete missing links.

4. CONCLUSIONS

This macro-scale study demonstrates that built environment interactions define four distinct TOD patterns across 64 Chinese and Latin American cities. The most significant finding is that medium-sized Latin American cities with intermediate node-place values show stronger alignment with TOD principles than their large or mega counterparts. They represent a realistic target for pedestrian-oriented interventions.

The use of a 400 m buffer at city level proved effective in capturing walkability potential, showing that even limited metro coverage can support TOD when density and land use mix are favorable. Policymakers in Cluster C4 cities should prioritize pedestrian corridors, feeder bus integration, and mixed-use zoning around existing stations. For Cluster C2 mega cities, strategic metro expansion is urgent. Cooperation between Latin America and China on mobility indicators and planning processes could accelerate progress toward SDG 11.

Limitations include uneven data temporality and the omission of intra-urban variations. Future research should incorporate walkability audits and cycling networks.

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