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Transportation Systems in Three Colombian Intermediate Cities: Identifying the Gap with the Smart, Sustainable, and Responsive Cities Paradigm

Luis Márquez ^{1,*} , Miguel A. Mendoza-Moreno ² , Luis A. Vega ¹, Juan C. Poveda ¹, Diana Angarita-Lozano ³ , Jeisson Tarazona ¹  and Lina Juliana Pulido ¹

¹ School of Transportation and Roads Engineering, Universidad Pedagógica y Tecnológica de Colombia, Tunja 150003, Colombia; luis.vega@uptc.edu.co (L.A.V.); juan.poveda@uptc.edu.co (J.C.P.); jeisson.tarazona@uptc.edu.co (J.T.); lina.pulido02@uptc.edu.co (L.J.P.)

² School of Systems and Computing Engineering, Universidad Pedagógica y Tecnológica de Colombia, Tunja 150003, Colombia; miguel.mendoza@uptc.edu.co

³ School of Environmental Engineering, Universidad Pedagógica y Tecnológica de Colombia, Tunja 150003, Colombia; diana.angarita@uptc.edu.co

* Correspondence: luis.marquez@uptc.edu.co

Abstract

This study examines how the transportation systems of three Colombian intermediate cities—Tunja, Barrancabermeja, and Neiva—diverge from the smart, sustainable, and responsive mobility paradigm. The analysis addresses a broader question: why global expectations for cyber-physical integration, low-carbon mobility, and adaptive governance remain difficult to achieve in resource-constrained urban contexts. Using a comparative, multi-dimensional assessment of modal structures, infrastructure continuity, digital readiness, environmental performance, and equity outcomes, the study evaluates each city through five analytical dimensions. The results show consistent systemic gaps: limited digital and analytical capacity, persistent fossil-fuel dependence, weak multimodal integration, fragmented governance, and uneven accessibility across socioeconomic groups. These gaps indicate that the challenge is not a lack of mobility but the absence of coordinated systems capable of transforming diverse practices into integrated, data-driven, and environmentally aligned networks. The findings demonstrate that territorial and socioeconomic contexts shape distinct expressions of shared structural constraints, underscoring that smart and sustainable mobility depends on aligning technological innovation with governance maturity, institutional interoperability, and lived mobility realities. The study provides an empirical baseline and a conceptual lens for rethinking mobility transitions in intermediate cities.

Keywords: smart mobility; intermediate cities; urban transportation systems; multimodal integration; digital governance; environmental sustainability; responsive urbanism; Colombia



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1. Introduction

The global shift toward urban sustainability has made mobility systems central to contemporary urban development, given their role in managing demographic growth, expanding service demands, and shaping environmental and social outcomes. Although metropolitan regions often lead these transformations, intermediate cities—typically ranging from 50,000 to 500,000 inhabitants—now face acute pressures associated with rapid and often unplanned urbanization, limited institutional capacity, and fragmented transport

governance [1]. In Latin America, these challenges are intensified by the prevalence of informal transit networks and persistent digitalization gaps, which collectively hinder the transition toward cohesive and modern mobility frameworks [2].

In parallel, the “smart, sustainable, and responsive” paradigm has emerged as a global benchmark for future-oriented urban planning, emphasizing the integration of AI- and IoT-enabled systems to enhance logistical efficiency, accessibility, and environmental performance [3,4]. Yet a clear misalignment persists between this paradigm and the structural realities of Colombian intermediate cities, where legacy infrastructure, socioeconomic constraints, and institutional fragmentation often render high-end smart-city interventions unfeasible [5,6]. This disconnect limits the potential of data-driven governance to improve resource management, public transport accessibility, and environmental performance.

Addressing this gap requires examining how global aspirations for cyber-physical adaptability interact with the pragmatic requirements of local transit systems. This study contributes to this need by systematically evaluating the transportation systems of Tunja, Barrancabermeja, and Neiva against the principles of the smart, sustainable, and responsive city model. Through a comparative, multi-dimensional assessment, the article identifies structural gaps in digital capacity, environmental performance, multimodal integration, institutional responsiveness, and social equity, clarifying the friction between universalist smart-city frameworks and context-dependent mobility realities [7].

Beyond diagnosing misalignments, the study advances a contextualized framework for understanding mobility in intermediate cities, emphasizing intergenerational equity, environmental resilience, and socio-technical entanglements as essential components of future planning [8,9]. The findings underscore that the success of smart mobility initiatives depends less on deploying novel technologies than on aligning digital tools with governance practices, resource capacities, and institutional maturity [10,11]. This perspective challenges assumptions of uniform technological scalability and highlights the risks of adopting standardized policy templates without accounting for local variations and institutional fragmentation [12,13].

The analysis shows that sustainability and intelligence are not inherent attributes of urban technologies but strategic choices that must align with local development trajectories [14]. By illustrating how niche pilot interventions often fail to scale into systemic reforms, the study stresses the importance of linking technology adoption to broader fiscal, environmental, and governance pressures. Achieving truly responsive mobility requires moving beyond fragmented technology pilots toward integrated governance mechanisms that harmonize institutional readiness with data-driven decision-making [15]. This approach prioritizes human capital, collaborative institutional structures, and the alignment of digital innovation with the social fabric, ensuring that infrastructure investments reduce systemic inequities rather than deepen the divide between technocratic aspirations and operational realities [8,16].

Grounded in the empirical realities of secondary Colombian municipalities, this article contributes an analytical lens that helps scholars and practitioners move beyond technocentric urbanism toward governance structures capable of supporting long-term urban resilience [17–19]. In doing so, it underscores the critical role of systemic interoperability, as siloed, project-based deployments continue to hinder the emergence of cohesive, data-informed mobility networks [20,21]. Ultimately, navigating the transition toward smart, sustainable, and responsive mobility requires prioritizing institutional capacity-building over the superficial integration of digital tools [13,22].

To address this disconnect, the study poses a specific research question: whether the smart, sustainable, and responsive mobility paradigm can adequately describe mobility conditions in Colombian intermediate cities or whether these conditions reveal a structural gap the paradigm does not capture. Accordingly, the article examines three questions: (i) how digital, environmental, multimodal, institutional, and equity dimensions manifest in each city; (ii) whether these dimensions interact to produce a systemic rather than isolated mobility gap; and (iii) how territorial context shapes differentiated expressions of shared constraints. These questions define empirical and analytical criteria through which the paradigm can be validated, challenged, or refined.

Recent evidence underscores the structural nature of mobility deficits in Global South cities, where rapid urbanization—expected to reach 68% of the world’s population by 2050—intensifies infrastructure strain, resource scarcity, and inequality [11]. In these settings, limited institutional capacity weakens governance, and mobility initiatives often advance without integrating informal transport, despite its high modal share in many intermediate cities [11]. Digitalization faces steep barriers: deploying sensors, communication networks, and charging infrastructure remains costly, while congestion, affordability, and road-safety challenges persist, with fatality rates in several Latin American intermediate cities exceeding global averages [3]. Even where digital platforms exist, benefits accrue unevenly—studies in Chengdu show that 60% of elderly residents avoid digital tools and satisfaction among high-income users is markedly higher than among low-income groups, illustrating persistent digital divides [8,19]. Accessibility gaps also remain pronounced, as over one billion people with disabilities continue to face systemic exclusion from transport systems, particularly in developing regions [4]. Meanwhile, environmental pressures—rising emissions, aging vehicle fleets, and deteriorating air quality—continue to intensify [6]. Although smart mobility promises integrated networks that reduce congestion and environmental impact [13], real-world implementation remains fragmented and uneven [19]. These conditions delineate a persistent gap between the data-rich, inclusive, and ecologically responsive infrastructure assumed by the smart–sustainable–responsive paradigm and the realities of intermediate cities, reinforcing the need for the comparative analysis developed in this study.

Beyond the Colombian context, this study’s findings offer broader reference value for intermediate cities worldwide facing similar constraints in data availability, institutional fragmentation, and resource-limited mobility planning. By deconstructing how systemic gaps emerge across digital, environmental, multimodal, governance, and equity dimensions, the analysis provides a transferable framework that can help other cities identify structural misalignments between global smart-mobility paradigms and local operational realities. This comparative lens is particularly relevant for municipalities in Latin America, Africa, and Asia where rapid urbanization, informal transport dynamics, and limited analytical capacity similarly challenge the feasibility of cyber-physical integration and low-carbon transitions.

2. The Smart, Sustainable, and Responsive Cities Paradigm

The smart, sustainable, and responsive city paradigm serves as a tripartite framework that addresses the escalating complexities of modern urbanization by integrating technological innovation, environmental stewardship, and institutional agility. This paradigm has gained global prominence over the past decade as a necessary evolution to manage the non-linear, emergent interactions inherent in contemporary urban systems [15].

2.1. Smart Cities

At its core, the smart city dimension relies on advanced digital ecosystems—encompassing Internet of Things (IoT) sensors, artificial intelligence, and real-time analytics—to transform raw urban data into actionable insights for mobility planning and public service delivery. By fostering interoperability across disparate urban subsystems, these cyber-physical frameworks enable evidence-based decision-making that optimizes resource allocation and mitigates service inefficiencies [6]. Through this integration, cities build interconnected networks that improve logistical precision and infrastructure performance, forming the foundation for complex urban operations [3].

Ensuring the scalability and transparency of these systems requires robust data governance and unified communication standards to prevent fragmented or siloed infrastructures [4,13]. When cities successfully break down these silos, they transition from isolated local optimizations to systemic, city-wide intelligence supported by deep perception capabilities [23]. This digital layer functions as an intelligent backbone that enables predictive modeling and real-time monitoring of urban conditions, allowing municipal authorities to proactively manage volatility through high-fidelity, sensor-driven oversight [5].

Beyond these mechanisms, effective smart city implementation hinges on leveraging AI and AIoT to enhance energy efficiency and reduce resource consumption [24]. Cyber-Physical Systems (CPS) further strengthen this capacity by enabling real-time data acquisition and adaptive control, facilitating the shift from static infrastructure to dynamic, responsive urban environments [25]. Achieving truly intelligent urban management requires convergent intelligence across sensing, control, and security systems, transforming traditional data collection into contextualized, real-time awareness. These multilayered architectures—spanning infrastructure-level IoT sensors to intelligence-driven application layers—bridge the physical and digital domains to ensure proactive, data-informed governance [21].

2.2. Sustainable Cities

The sustainable city dimension emphasizes a transition toward low-carbon mobility, circular resource metabolism, and climate-aligned urban planning that integrates environmental justice with socioeconomic equity. By expanding active transport networks and accelerating the electrification of mobility systems, cities can reduce their carbon footprints while strengthening long-term resilience [23]. Sustainability also requires a shift toward regenerative urban design, where resource flows become circular, and infrastructure development actively mitigates climate-induced environmental degradation [12]. By integrating green technologies and ecological infrastructure, cities can strengthen their adaptive capacity to climate variability while addressing the intrinsic link between resource efficiency and equitable access to urban services [8,11].

However, this commitment to sustainability extends beyond carbon reduction, aligning ecological imperatives with the social fabric to keep environmental justice central to urban development [6]. In this sense, sustainable cities prioritize not only emissions mitigation but also creating inclusive, regenerative environments that support intergenerational well-being.

2.3. Responsive Cities

Responsive cities place institutional adaptability, anticipatory governance, and citizen-centered decision-making at the core of urban development, using participatory mechanisms and continuous feedback to align public action with evolving social, environmental, and mobility needs [26]. By fostering these feedback loops, cities can turn heterogeneous

IoT data streams into actionable insights that optimize resource allocation and improve service delivery [27]. This synthesis creates a robust feedback architecture in which real-time diagnostics—such as those used in multi-stakeholder pilot programs—ensure infrastructure upgrades align directly with the needs of vulnerable urban sectors [20].

Through virtual replicas and dynamic simulation environments, planners can anticipate bottlenecks and stress-test urban responses before implementation, shifting planning from static, linear processes to agile, iterative cycles [28]. This predictive capacity enables administrators to recalibrate service delivery in response to demographic fluctuations, acute crises, or emerging mobility pressures [11]. Such adaptive governance models draw on complex systems theory, which posits that urban resilience emerges from the self-organization of energy flows and the continuous calibration of regulatory frameworks to environmental and social stimuli [29]. As a result, responsiveness becomes defined not by rigid master plans but by a city's ability to absorb, recover from, and evolve in the face of socio-economic or environmental shocks [5].

Furthermore, the responsive dimension underscores that urban resilience is not merely a technical achievement but a governance capacity—one that depends on transparent procedures, robust data protection, and inclusive participatory channels to prevent technological bias or exclusionary practices [19]. When combined with the smart and sustainable dimensions, responsiveness ensures that technological deployment remains aligned with public interests, ecological imperatives, and the lived experiences of diverse urban populations.

2.4. Integrating and Connecting the Smart, Sustainable, and Responsive Paradigm to Mobility Systems

Integrating smart, sustainable, and responsive dimensions creates a reinforcing feedback system in which digital intelligence provides the analytical depth needed for ecological stewardship and institutional agility [30]. ICT-enabled diagnostics offer granular visibility to refine resource flows and support real-time adjustments essential for participatory governance [7,31]. Harmonizing these domains allows cities to move beyond isolated automation toward integrated ecosystems where data-driven awareness informs control mechanisms and keeps technological adoption aligned with human-centered resilience. As these systems evolve, technological deployment and institutional governance codevelop to manage the volatility of contemporary urban environments [15].

Digital twins in Intelligent Transportation Systems (ITS) exemplify this nexus by improving transit efficiency and reducing carbon footprints through predictive, demand-responsive operations [32]. The convergence of artificial intelligence and cyber-physical systems helps administrators evaluate spatial dependencies and ensure that sustainability interventions remain cost-effective and equitable [25]. This multi-scalar logic reconciles rapid technological change with long-term urban balance [13], prioritizing resilience over isolated coordination. A persistent challenge, however, is navigating causal complexity without conflating technological means with the broader goals of sustainable development [14].

In mobility systems, this integrative logic shifts transportation from static infrastructure to dynamic, service-oriented ecosystems [33]. Digital twins enable real-time monitoring of traffic and transit performance, supporting optimization of routing, operations, and environmental impacts [28]. AI-based identification models enhance congestion detection and enable demand-responsive solutions that reduce reliance on carbon-intensive modes [34]. Recent advances also include explainable efficiency-assessment models for public transport, such as DEA-based approaches that integrate XAI techniques to interpret performance across origin–destination pairs [35]. Through this multidimensional strategy, electrification

and multimodal integration become synchronized via data-centric planning to improve air quality and social equity [36].

Connecting the paradigm to mobility also requires governance reforms that address ownership, accessibility, and accountability in digital transport platforms [37]. Transparent data governance helps overcome public resistance and ensures that decision-making prioritizes inclusive access. Aligning technological solutions with evidence on user accessibility needs helps ensure that digital platforms and mobility services support more equitable connectivity for vulnerable populations [38]. This evolution demands moving beyond siloed, mode-specific infrastructure toward frameworks that synthesize multi-source data for diverse user needs [4].

Edge-computing networks further strengthen this architecture by enabling latency-sensitive operations locally and supporting rapid implementation of demand-responsive policies without centralized vulnerabilities [39]. Interoperable and scalable systems allow municipalities to manage interdependencies across energy, safety, and transport, creating cohesive digital environments for adaptive urban management [21]. Ultimately, integrating smart, sustainable, and responsive dimensions transforms mobility into a core driver of urban resilience—combining digital intelligence, ecological imperatives, and governance agility within a unified operational logic.

3. Materials and Methods

3.1. Study Design

This research adopts a comparative multi-case study design to examine how transportation systems in three Colombian intermediate cities diverge from the smart, sustainable, and responsive mobility paradigm. The study combines descriptive characterization with analytical comparison across five dimensions—digital and analytical capacity, environmental performance, multimodal integration, institutional responsiveness, and social equity—to identify the structural nature of the mobility gap.

To operate the five assessment dimensions, the study employed a structured qualitative-comparative procedure rather than a weighted scoring model. The study evaluated each dimension using a set of observable indicators—digital governance practices, environmental performance metrics, multimodal continuity, institutional coordination mechanisms, and equity-related accessibility conditions—derived from municipal plans, technical reports, and national datasets. We determined alignment with the smart–sustainable–responsive paradigm by assessing whether indicators met baseline functional criteria: interoperable data standards, evidence of emissions-reduction or fleet-renewal efforts, continuity across modal networks, formalized coordination arrangements, and accessibility provisions for vulnerable groups. We identified misalignment when indicators were absent, fragmented, or inconsistent across sources. This approach allows for transparent comparative judgments while acknowledging the heterogeneity and discontinuity of available data across the three cities.

Indicator selection followed a structured procedure grounded in relevance to each analytical dimension, measurability across the three cities, and consistency with the functional criteria of the smart–sustainable–responsive paradigm. Indicators were assigned to dimensions based on their conceptual alignment with digital capacity, environmental performance, multimodal continuity, institutional coordination, and social equity. Because the study relies on heterogeneous secondary data and compares cities with different institutional capacities, no numerical thresholds, weights, or scoring rules were applied. Instead, the assessment identifies structural patterns of convergence or divergence across dimensions, ensuring transparency and reproducibility while avoiding artificial precision unsupported by the available evidence.

3.2. Case Selection

The selection of Tunja, Barrancabermeja, and Neiva followed three criteria:

- Population scale: All three cities fall within the commonly accepted range for intermediate cities (50,000–500,000 inhabitants), ensuring analytical comparability.
- Functional diversity: The cases represent distinct territorial and economic configurations—an Andean administrative center (Tunja), an industrial and port district (Barrancabermeja), and a regional commercial hub in the Magdalena valley (Neiva).
- Availability of mobility-related information: Each city has mobility studies, fleet inventories, environmental indicators, and planning documents that provide a minimum common basis for extracting comparable data, even though the temporal coverage and methodological robustness of these sources vary.

These three cities were selected not only because they meet the population and functional criteria but because they represent typical structural conditions found in intermediate cities across Colombia and other regions of the Global South. Tunja, Barrancabermeja, and Neiva exhibit common mobility challenges—such as limited analytical capacity, modal fragmentation, informal transport dynamics, and constrained environmental monitoring—while also reflecting diverse territorial, economic, and institutional contexts. This combination of shared structural constraints and differentiated local expressions makes them analytically representative cases for examining how systemic mobility gaps emerge in resource-limited urban environments. Their selection therefore strengthens the study's comparative value and supports the generalizability of its findings to similar intermediate cities worldwide.

3.3. Data Sources

The analysis draws up secondary data from official and technical sources, including:

- Municipal mobility plans and diagnostic studies (e.g., origin–destination surveys, fleet inventories, route analyses).
- Environmental monitoring reports (air quality, emissions, particulate matter).
- Road-safety statistics from municipal and national agencies.
- Planning and regulatory documents related to public transport operations, infrastructure, and land use.
- The academic literature on smart mobility, sustainable transport, and responsive urban governance.

All documents were reviewed systematically to extract quantitative indicators (e.g., mode share, fleet age, emissions, road-safety rates) and qualitative evidence (e.g., governance arrangements, institutional fragmentation, infrastructure continuity).

3.4. Period of Reference

The empirical analysis covers the period 2015–2023, corresponding to the availability of mobility plans, environmental reports, fleet inventories, and road-safety statistics in the three cities. When multiple versions of a document existed, the most recent and methodologically robust source was used. This temporal scope applies exclusively to the empirical data; the literature review is not restricted to this period and incorporates the most recent scientific contributions relevant to smart, sustainable, and responsive mobility.

Although the general reference period spans 2015–2023, each indicator's exact year varies slightly across the three cities because municipal mobility studies, fleet inventories, and environmental reports differ in timing and frequency. To ensure comparability, we used only indicators with methodological equivalence, and when multiple years were available,

we selected the most recent and methodologically robust source within the 2015–2023 window for each city.

3.5. Data Collection and Extraction

A structured document-review protocol was applied:

- Identification of relevant sources through municipal repositories, planning offices, and publicly available technical studies.
- Extraction of mobility indicators using a standardized template covering modal composition, infrastructure conditions, digital readiness, environmental performance, and equity implications.
- Cross-validation of extracted information by comparing multiple sources when available (e.g., fleet inventories vs. environmental reports).

This procedure ensured consistency in the analytical inputs used for comparison.

3.6. Analytical Framework

The comparative analysis is structured around the smart, sustainable, and responsive mobility paradigm, operationalized into five analytical dimensions:

- Digital and analytical capacity
- Environmental sustainability
- Multimodal integration
- Institutional responsiveness and governance
- Social equity and accessibility

For each dimension, indicators were interpreted qualitatively and quantitatively to assess the degree of alignment or misalignment with the paradigm. The analysis emphasizes structural relationships—how modal fragmentation, institutional arrangements, environmental pressures, and data limitations interact to produce systemic gaps.

3.7. Comparative Procedure

The comparison followed a three-step procedure:

- Within-case analysis: Each city was characterized independently to identify its mobility structure, constraints, and institutional context.
- Cross-case comparison: Findings were contrasted across cities to identify common patterns and context-specific divergences.
- Synthesis: The results were integrated to determine the systemic nature of the mobility gap and its implications for smart, sustainable, and responsive transitions.

This procedure aligns with established comparative-urban methodologies and supports the article's interpretive conclusions.

3.8. Limitations

The study faces some methodological considerations that should be acknowledged. Data availability varies across the three cities, particularly regarding informal transport services and real-time operational information. Municipal mobility studies differ in measurement years and methodological approaches, requiring careful cross-checking during data extraction. Environmental monitoring infrastructure is limited—especially in Neiva and Barrancabermeja—reducing the temporal and spatial resolution of emissions and air-quality indicators. In addition, the lack of continuous origin–destination data limits dynamic modeling of travel patterns and reduces the precision of accessibility analysis. These considerations do not undermine the comparative assessment; they reflect structural

conditions typical of intermediate cities and reinforce the study's central argument about limited analytical capacity.

Despite these constraints, the validity of the cross-city comparative conclusions is maintained through structurally equivalent indicators and methodological triangulation. The comparison included only data sources with comparable definitions, measurement criteria, and analytical scope, even when their years differed. When continuous data were unavailable, we used convergence across multiple independent sources to validate trends and structural conditions. This approach ensures that the comparative findings reflect systemic patterns rather than isolated numerical variations, and it aligns with the study's central argument that limited analytical capacity is itself a structural characteristic of intermediate cities.

4. Results

4.1. Empirical Characterization of Transportation Systems in Three Colombian Intermediate Cities

Understanding transportation systems in Colombian intermediate cities requires examining how territorial form, socioeconomic dynamics, modal cultures, institutional capacities, and environmental pressures shape everyday mobility. Unlike large metropolitan areas, cities such as Tunja, Barrancabermeja, and Neiva (Figure 1) display mobility structures constrained by historical urban form, influenced by industrial specialization, and reshaped by rapid peripheral expansion. Their systems combine formal and informal modes, uneven digitalization, heterogeneous infrastructure, and distinct environmental burdens, producing mobility outcomes that diverge markedly from the smart, sustainable, and responsive city paradigm.

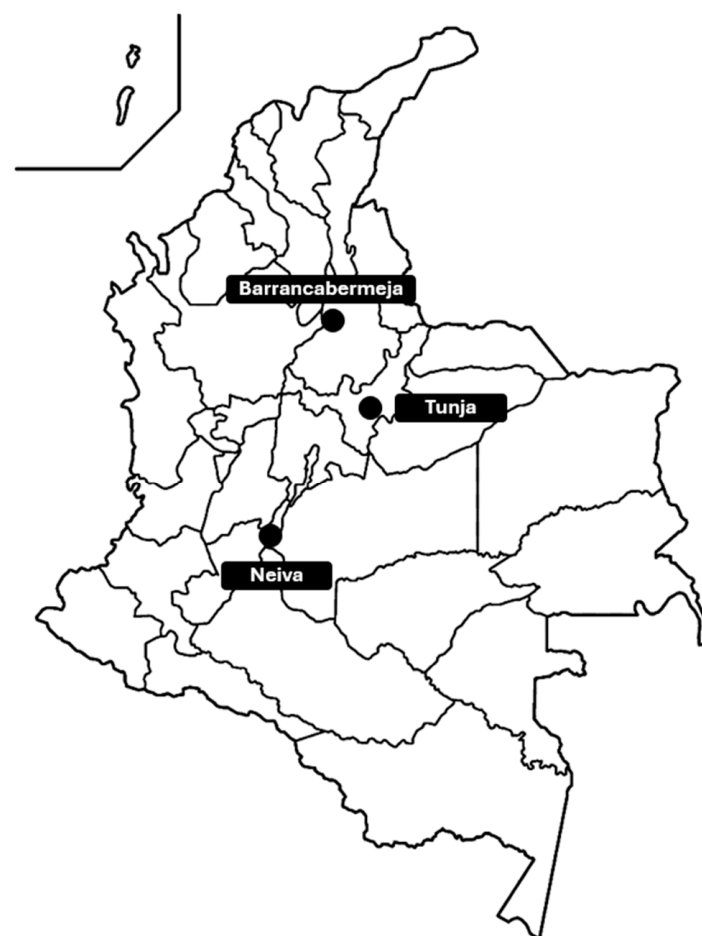


Figure 1. Location of the three cities under study.

By characterizing each city's modal composition, infrastructure continuity, governance arrangements, environmental performance, and equity implications, this section establishes the empirical foundation necessary to identify the structural gap between current mobility realities and the requirements of future-ready urban systems.

4.1.1. The Case of Tunja

With an estimated population of 189,000 inhabitants, Tunja is an intermediate Andean city and the capital of Boyacá, whose administrative, educational, cultural, and service functions generate substantial daily travel demand beyond its residential population. Founded in 1539 and located at approximately 2800 m above sea level, the city developed around a historically consolidated urban fabric characterized by steep slopes, irregular blocks, and a constrained historic center. These physical and historical conditions limit the feasibility of widening streets or introducing large-scale transport infrastructure, producing a mobility structure in which short trips remain competitive by walking, while longer trips concentrate along a small number of connecting corridors.

Available mobility evidence confirms this duality: walking accounts for about 36% of trips, while urban collective public transport accounts for about 35%, with 104,725 daily trips and an estimated passenger-kilometer index of 1.5 [40]. Tunja therefore relies more on collective transport and walking than the other cities in the comparison, where motorcycles do not play the dominant role, they assume in many Colombian intermediate cities. Private automobiles, taxis, and conventional collective services nevertheless remain important components of the system, particularly for trips requiring greater speed, comfort, or access to areas inadequately served by scheduled routes.

The public transport system is structured around traditional urban collective services that link peripheral residential areas to central employment, education, commercial, and institutional destinations. Its high demand underscores its importance for students, low-income households, and users without private vehicles, though usage alone does not imply full reliability or integration. The route network reflects Tunja's linear, topographically constrained expansion, concentrating flows on central and peripheral corridors and heightening exposure to congestion, delays, and service irregularity. Although the fleet incorporates GPS and passenger-counting sensors that support monitoring, incident reporting, speed control, and demand analysis, these tools do not yet translate into a user-oriented ITS or seamless operational coordination among municipal authorities and operators.

The road network reflects the interaction between historical preservation and metropolitan expansion. The narrow streets and limited internal capacity of the historic center discourage high-volume flows, encouraging a ring-like or semi-peripheral circulation logic along key avenues such as Maldonado, Colón, Suárez Rendón, and Oriental. This configuration channels movements around the historic core and distributes flows between central and outlying areas while concentrating pressure at junctions and access points. As urbanization extends into peripheral sectors, travel distances lengthen and dependence on motorized modes grows, especially where pedestrian continuity and frequent public transport are weak.

Pedestrian mobility remains an essential asset of Tunja's compact central areas, yet its performance depends on sidewalk quality, crossings, slopes, lighting, and universal-access treatments. Steep terrain, discontinuous pedestrian paths, conflicts with vehicle access, and perceptions of traffic insecurity can convert walking from an efficient mode for short trips into a physically and socially differentiated option. Cycling has significant potential as a low-carbon complement to walking and collective transport, but the continuity and quality of bike lanes and shared spaces remain insufficient to establish a coherent city-

wide network. Although bicycle ownership in Tunja is comparatively high, much of this ownership reflects recreational rather than daily transport use; topography, road-safety concerns, limited protected infrastructure, and a mobility culture historically oriented toward buses, taxis, and cars constrain broader adoption and help explain the gap between ownership and regular utilitarian cycling.

Tunja's readiness for smart mobility remains partial rather than systemic. The absence of recent specialized mobility surveys means the city still lacks a stable, regularly updated data foundation for origin–destination analysis, demand forecasting, accessibility assessment, and evidence-based service redesign. Existing onboard technologies support fleet monitoring, but their effectiveness depends on interoperability, data standards, institutional capacity, and operators' willingness to share information with public agencies and users. Current evidence does not show a consolidated public platform for real-time arrival information, integrated trip planning, digital payment, or open mobility data; digitalization therefore remains closer to operational tracking than to an integrated ITS. This gap is reinforced by fragmented responsibilities across municipal administration, transport authorities, operators, and regional actors, each holding only part of the information required for coordinated planning.

Environmental performance reveals persistent structural limitations. The emissions profile of the evaluated systems reflects a continued dependence on fossil fuels, as evidenced by CO₂ emission factors of approximately 55.4 tons per vehicle per year and 512 g/km. These values illustrate the high carbon intensity of conventional operations and the reliance on internal-combustion technologies. In parallel, environmental monitoring data highlight exposure conditions shaped by traffic emissions, fleet age, congestion, and meteorological dynamics, underscoring the cumulative environmental burden associated with outdated propulsion systems [40]. Congestion in central and connecting corridors intensifies these effects by reducing operating efficiency and increasing idling and stop-and-go conditions. Although planning initiatives articulate sustainable and inclusive objectives, the limited penetration of cleaner technologies, absence of comprehensive multimodal integration, and small reported reduction in emissions attributable to green policies demonstrate a substantial distance between policy ambition and system performance.

These limitations also have an equity dimension. Central districts and areas near major educational and institutional destinations benefit from greater proximity to services and more direct transport connections, whereas peripheral residents face longer journeys, additional transfers, and greater uncertainty when routes or frequencies do not adequately respond to dispersed demand. The system's heavy reliance on collective transport and walking suggests mobility is broadly accessible, but aggregate mode shares conceal differentiated burdens tied to fares, travel time, physical effort, unreliable connections, and vehicle accessibility. Students depend heavily on affordable and frequent services; older adults and people with disabilities are more sensitive to sidewalk conditions, boarding arrangements, and the absence of integrated information; and low-income households are particularly vulnerable to service disruptions due to fewer private alternatives.

Tunja therefore combines strong social dependence on conventional collective transport and walking with a road system constrained by topography and historical form, an aging fossil-fuel fleet, discontinuous active-mobility infrastructure, and an incomplete digital and institutional platform. Its relatively high public-transport and walking shares distinguish it from more motorcycle-dependent intermediate cities, but they should not be mistaken for evidence of a smart, sustainable, and responsive system. The principal weaknesses lie in limited modal integration, insufficiently accessible data, weak translation

of vehicle-level monitoring into public intelligence, uneven peripheral accessibility, and slow environmental modernization of the fleet.

4.1.2. The Case of Barrancabermeja

Barrancabermeja, unlike high-altitude Tunja, is a lowland intermediate city shaped by its position along the Magdalena River, its extensive territorial jurisdiction, and its strategic role as Colombia's principal oil-refining center. With a population of roughly 210,000 inhabitants, an elevation of about 75 m above sea level, a municipal area exceeding 1100 km² [41], and climatic conditions that can generate heat sensations approaching 39 °C, the city was designated in 2019 as a Special District of Port, Industry, Tourism, and Biodiversity. Its urban economy remains strongly dependent on the Ecopetrol refinery, although commerce, services, logistics, tourism, and other activities also contribute to employment and local circulation.

This industrial specialization produces a spatially differentiated mobility structure. Residential neighborhoods, commercial areas, riverfront and port activities, peripheral settlements, and industrial facilities generate concentrated and often time-specific flows, particularly among workers travelling to refinery and logistics zones. Mobility demand is therefore shaped not only by population size but also by shift-based employment, freight movements, industrial access controls, and the uneven distribution of housing and services.

Barrancabermeja's mobility differs sharply from Tunja's. Motorcycles and motorcycle taxis dominate short and medium trips, while buses, taxis, informal vans, and private cars operate in a fragmented market. Before the pandemic, over 350 buses and minibuses circulated—about a quarter of the registered fleet—but only a third remained active later. Motorcycle-taxi demand nearly matches collective transport, showing that informal mobility is structurally embedded. Although private-car ownership is lower than in Tunja and Neiva, automobiles still play a significant role in everyday mobility, particularly for trips requiring comfort, speed, or access to areas with limited public-transport coverage. Walking is constrained by heat, safety risks, and poor pedestrian infrastructure.

Motorcycle taxis and informal vans fill spatial and temporal gaps, especially in peripheral areas, but complicate regulation, safety monitoring, accident reporting, and demand estimation. Their exclusion from official databases makes their role visible in practice but difficult to integrate into planning. Although flat terrain favors active mobility, cycling and walking remain limited by discontinuous infrastructure, lack of shade, heat, insecurity, and interaction with industrial traffic; perceived risk and motorized dominance further constrain bicycle adoption.

Spatial segregation reinforces these limitations. Industrial land uses and large-scale infrastructure interrupt direct connections between residential areas and employment, while peripheral communities experience longer or less predictable journeys to educational, health, and commercial services. Transport expenditure reaches roughly a quarter of household budgets among low-income families—defined here as households in socioeconomic strata 1 and 2 according to Colombia's official classification—based on microdata for Barrancabermeja ($n = 4312$ households), from which the indicator was calculated as the ratio between monthly transport spending and total household expenditure. This pattern indicates that nominal affordability does not guarantee equitable accessibility, as transport costs continue to impose a disproportionate burden on the most economically vulnerable groups. Students benefit from municipal subsidies for public transport, but the broader system still leaves workers, older adults, persons with disabilities, and peripheral residents exposed to deficient frequency, unsafe boarding conditions, limited information, and the need to combine several modes.

Digitalization remains incipient. Current documentation does not document a consolidated public system for real-time vehicle location, integrated payment, passenger information, or multimodal route planning. Instead, GPS-based fleet management, real-time passenger-information systems, electronic payment, and central monitoring appear primarily as recommended components for future implementation rather than established capabilities. This distinction matters analytically: proposed technologies should not be confused with operational smart-mobility readiness.

Barrancabermeja also faces a pronounced data-governance deficit. Discrepancies between historical route inventories and currently operating services, together with the need to repeat origin–destination surveys, indicate that planning relies on incomplete or outdated information. Coordination among municipal authorities, transport regulators, formal operators, informal providers, port and industrial stakeholders, and Ecopetrol is necessary, yet current documentation does not demonstrate the existence of unified data architecture or jointly managed mobility demand.

Environmental performance reveals a structural contradiction in Barrancabermeja's mobility system. Despite operating with relatively moderate CO₂ emission factors—38.9 tons of CO₂ per vehicle annually and 480 g/km—the city shows only marginal reductions attributable to green-policy interventions [42]. These conditions reflect the combined influence of transport activity, refinery-related emissions, and industrial operations, while the large motorcycle fleet further contributes to local exhaust pollutants, noise, and heightened vulnerability among road users. Consequently, Barrancabermeja's sustainability challenge extends beyond fleet electrification and cleaner fuels: it requires integrated freight-management strategies, climate-responsive infrastructure, shaded active-mobility corridors, and stronger coordination between industrial and urban environmental-monitoring systems.

Road safety is likewise a central social concern, with 31 traffic deaths per 100,000 inhabitants in Barrancabermeja, according to the National Institute of Legal Medicine and Forensic Sciences [43]. Barrancabermeja thus presents a transportation system in which the apparent flexibility of motorcycles and motorcycle taxis compensates for the decline and uneven coverage of formal buses, while industrial specialization concentrates flows and environmental risks in particular corridors.

Its main divergence from the smart, sustainable, and responsive city paradigm lies in the coexistence of modal fragmentation, informal competition, incomplete peripheral accessibility, weak active-mobility provision, fossil-fuel dependence, and limited digital and institutional integration. The case therefore lacks a coordinated system that can convert diverse mobility practices, industrial demands, and territorial inequalities into shared data, reliable services, and equitable environmental performance.

4.1.3. The Case of Neiva

Founded in 1612 and serving as the capital of Huila, Neiva functions as a regional center for commerce, services, agriculture, livestock marketing, higher education, and tourism. Neiva has a projected population of 408,218 inhabitants. Its position in the Magdalena valley connects the southwestern Andean region with surrounding departments and national markets, while its warm climate—characterized by temperatures between 28 °C and 37 °C—and marked seasonal rainfall influence travel times, thermal comfort, and modal preferences. The city's location between the Central and Eastern cordilleras and near the Magdalena River provides strategic territorial connectivity but also exposes roads, drainage systems, and peripheral settlements to climatic and hydrological stress, particularly where expansion has occurred without equivalent investment in resilient infrastructure.

These conditions shape mobility choices in a decisive way. High temperatures and solar exposure reduce the attractiveness of walking and cycling for everyday trips, while motorcycles offer speed, door-to-door flexibility, and relatively low operating costs across an expanding urban territory. As a result, Neiva's mobility culture is markedly motorized. Motorcycles account for roughly 40% of trips—an estimated 187,000 daily journeys, making them the dominant mode. Although official records list 23,076 motorcycles registered in Neiva, mobility authorities estimate that more than 120,000 circulate daily. This discrepancy results from the widespread practice of registering vehicles in neighboring municipalities such as Rivera and Palermo. Therefore, modal shares reflect operational circulation rather than formal registration.

Urban collective transport represents only about 20% of trips [44], a considerably lower share than in Tunja or Barrancabermeja. The city also records comparatively high use of taxis, suggesting that conventional public transport does not adequately satisfy demand for flexible or geographically extensive service. Private automobiles, conventional buses, taxis, motorcycle taxis, informal vans, and walking coexist in a fragmented modal structure in which the motorcycle is not merely an alternative but a substitute for unreliable or poorly connected collective transport.

Spatial patterns accentuate Neiva's fragmented mobility. Central districts, with shorter distances and concentrated services, rely more on walking, taxis, and formal buses, though congestion remains high. Peripheral settlements depend on motorcycles, motorcycle taxis, and informal vans because of longer distances, poor pedestrian conditions, and limited bus frequency. These choices reflect climate, income, informality, and service quality rather than cultural preference: motorcycles reduce waiting and transfer costs but increase exposure to crashes, noise, and emissions.

The formal system consists mainly of minibuses operated by several companies. Although the nominal fleet is large, effective capacity is limited by vehicle availability and uneven operation: 390–410 vehicles ran on weekdays, around 300 on Saturdays, and only 145 on Sundays, while many authorized vehicles remained inactive. The fleet is dominated by 19-passenger minibuses, more than half of which are over ten years old [44]. Overlapping routes, irregular frequencies, inefficient vehicle allocation, and congestion create long, unpredictable trips, leaving peripheral and low-income areas particularly vulnerable.

Evidence shows oversupply in some corridors and ineffective routes elsewhere, revealing a mismatch between fleet size and service quality. Motorcycle taxis and informal vans fill these gaps by offering rapid, flexible connections, especially in peripheral neighborhoods and low-service periods. Their contribution to accessibility is substantial but hard to integrate into planning because of limited records, weak regulation, and concerns about safety, vehicle condition, insurance, and accountability.

Neiva's road network reflects pressures from modal imbalance and rapid urbanization. Only part of its extensive road system is paved, and many corridors are in poor condition. Main roads must accommodate buses, motorcycles, cars, taxis, informal vehicles, loading activities, and pedestrians, generating recurrent bottlenecks. High motorcycle use increases traffic volatility, while informal stopping reduces effective capacity. Secondary roads in recently urbanized areas suffer from deficient paving, drainage, lighting, and maintenance, increasing travel-time variability and isolating communities during heavy rainfall. Urban expansion lengthens trips and raises the cost of providing efficient routes, making fixed-route buses less competitive than motorcycles and informal services.

Active mobility does not compensate for these disadvantages. Discontinuous sidewalks, inadequate crossings, limited shade, and weak protection from traffic hinder walking, especially for vulnerable groups. Cycling faces similar constraints: limited

continuity and protection of facilities, weak integration with public transport, heat exposure, insecurity, and a motorized mobility culture reduce adoption. The absence of a comprehensive active-mobility network reinforces dependence on motorcycles and taxis for short and medium trips.

Neiva's smart-mobility readiness remains limited, and its environmental indicators reinforce this constraint. Collective-transport vehicles emit 50.3 tons of CO₂ per year and 510 g/km, alongside average noise levels of 70 dB and only 7% reductions attributable to green-policy measures [44]. Despite these pressures, the city lacks consolidated digital platforms for real-time bus location, integrated payment, multimodal journey planning, or coordinated fleet monitoring. Institutional fragmentation among operators, municipal authorities, and informal providers persists, reducing the effectiveness of operational management. Planning is further constrained by discontinuous or outdated data on demand, route performance, vehicle availability, informal services, and origin–destination patterns. Air-quality monitoring relies on only two stations and manual equipment, illustrating broader challenges in generating high-resolution evidence. Without interoperable data standards and sufficient institutional capacity, digital tools remain isolated applications rather than components of a responsive mobility system.

Environmental performance underscores the costs of current mobility. The collective-transport fleet relies on fossil fuels, and the dominant motorcycle fleet adds substantial emissions, noise, and vulnerability. Older vehicles hinder alignment with decarbonization goals, and the absence of electrification or clean-fuel strategies widens the gap with low-carbon models. Environmental burdens are spatially unequal: peripheral residents face poorer road conditions, greater exposure to dust and traffic, and heavier reliance on older or informal vehicles.

These conditions generate equity challenges beyond fares. Low-income households, informal workers, older adults, students, and people with disabilities face constraints in waiting time, physical access, off-peak service availability, safety, and the cost of reaching employment, education, and health services. Motorcycles reduce immediate travel burdens but shift significant risks and exclude those who cannot drive.

Neiva's mobility system thus relies on motorcycle dominance and informal flexibility to compensate for deficiencies in formal transport while deepening congestion, environmental impacts, safety risks, and institutional fragmentation. Its misalignment with the smart, sustainable, and responsive paradigm stems from high motorization, an aging fossil-fuel fleet, incomplete active-mobility infrastructure, uneven peripheral accessibility, limited digital integration, weak environmental monitoring, and insufficient coordination. The city is not immobile but adapts through individualized, hard-to-regulate practices, contrasting Barrancabermeja's industrial pressures and Tunja's topographic constraints and establishing a comparative basis for assessing gaps across urban contexts.

4.2. Structural Gap Between Existing Mobility Systems and the Smart–Sustainable–Responsive Paradigm

The structural gap identified in this article can be made visible only through a synoptic view of the indicators that define each city across the five analytical dimensions. Table 1 therefore compiles the demographic, fleet, environmental, and road-safety indicators for Tunja, Barrancabermeja, and Neiva, providing the empirical reference on which the comparative analysis in this section and the Discussion are built. Reading the table horizontally reveals the differentiated configuration of each city's gap; reading it vertically shows the uneven incidence of each dimension across the case set.

Table 1. Synthesis of key mobility indicators across Tunja, Barrancabermeja, and Neiva.

Category/Indicator	Tunja	Barrancabermeja	Neiva
Demographic Indicators			
Urban population density (hab/ha)	89.40	73.96	80.24
Educational Development Index ¹	0.751	0.682	0.703
Average household size	3.5	3.8	3.7
Number of households	55,679	61,967	101,646
Annual per-capita income (thousand USD, 2023)	4.8	5.2	4.76
Unemployment rate (2023)	9.7%	21.6%	10.1%
Informality rate (2023)	37.6%	43.8%	53.2%
Public Transport Fleet and Equipment Indicators			
Motorization rate (veh/1000 hab) ²	3.1	0.6	1.5
Seating capacity (seats/1000 hab)	59.8	21.7	27.1
Fleet age (share 10–20 years)	~60%	~50%	~60%
Fuel efficiency (km/gal)	19.25	N/A ³	17.0
Operating cost per km (COP/km)	918	N/A ³	1090
Vehicles per route	25.3	22.4	14.2
Vehicle Ownership (registered vehicles per 1000 inhabitants)			
Private vehicles	141	77	103
Bicycles	101	78	61
Motorcycles	41	347	58
Taxis	6.4	5.0	5.8
Environmental Sustainability Indicators			
CO ₂ emissions per public transport vehicle (ton/year) ⁴	55.4	38.9	50.3
CO ₂ emissions per vehicle (g/km)	512	480	510
Average noise level (dB)	72.5	71.0	70.0
Emission reduction from green policies (%)	5%	3%	7%
Fuel type	Fossil fuels	Fossil fuels	Fossil fuels
Road Safety Indicators			
Mortality rate (per 100,000 inhabitants)	17	31	19
Injuries per 100,000 inhabitants	130	88	109
Public transport-related mortality (per 100,000 inhabitants)	1.2	1.2	0.3
Passenger transport deaths and injuries (per 100,000 inhabitants)	5.8	3.5	1.6

¹ Composite indicator published by the Colombian Ministry of Education (educational attainment, progression, learning outcomes). ² Motorization rate (veh/1000 hab) refers exclusively to the number of public transport vehicles per 1000 inhabitants, not total registered vehicles. ³ Not available.

⁴ Calculated using fleet-specific emission factors and annual average distance traveled.

To ensure comparability across the three cities, we accompanied each empirical indicator with its reference year and data source, and we prioritized the most recent and methodologically consistent information available. When indicators differed in measurement year, we interpreted values within a harmonized comparison window (2018–2023), and used older data only when no updated equivalent existed. We addressed differences in municipal methodologies by cross-checking definitions, normalizing denominators, and verifying consistency across national datasets. This procedure reduces the risk that observed differences reflect temporal or methodological variation rather than genuine disparities in mobility performance.

The indicators in Table 1 anticipate the structural gap analyzed in the following section. Because municipal studies, fleet inventories, environmental reports, and road-safety datasets differ in methodological approach, we ensured comparability by selecting only indicators with equivalent definitions across cities, prioritizing sources with consistent measurement criteria, and cross-checking values when multiple documents were available. This harmonization procedure allowed indicators collected in different years and through

heterogeneous methodologies to be made sufficiently comparable for the purposes of the cross-city assessment.

Horizontally, each row reveals a distinct urban profile—Tunja’s stronger collective-transport supply and walking culture, Barrancabermeja’s industrial pressures, aging fleet, and exceptionally high motorcycle ownership, and Neiva’s dispersed form and modal imbalance. Vertically, the table shows that none of the cities performs consistently across demographic, fleet, ownership, environmental, or road-safety dimensions; instead, each cluster differently while converging on the same systemic deficiencies: fossil-fuel dependence, aging fleets, incomplete digital infrastructure, and concentrated exposure and safety burdens. The table thus provides the quantitative foundation for the five analytical dimensions developed below, framing these patterns not as isolated deficits but as interacting components of a single structural gap.

4.2.1. Digital and Analytical Capacity

The first dimension of the gap concerns the three cities’ limited capacity to observe, interpret, and manage mobility as a dynamic urban system. The smart-city paradigm presupposes integrating real-time data, interoperable platforms, predictive analytics, and cyber-physical coordination, allowing transport operations to adjust in response to changing demand, congestion, environmental conditions, and user needs. Digital twins and related systems are expected to link continuous operational monitoring with scenario simulation and long-term planning, creating feedback between immediate management and strategic decision-making [45]. The evidence from the three cities indicates that this condition has not yet been achieved.

Tunja shows elements of partial digitalization, but these do not form a unified ITS that integrates vehicle location, passenger demand, ticketing, traffic conditions, and environmental information. Barrancabermeja faces a more pronounced challenge because formal operators, informal providers, and industrial activities generate information through separate and weakly coordinated channels. In Neiva, the absence of a consolidated platform for real-time bus information, multimodal journey planning, integrated payment, and shared fleet or traffic management is compounded by discontinuous information on routes, demand, informal services, and origin–destination patterns.

In all three cases, the result is not simply a shortage of technology but a deficit of analytical capacity: data are incomplete, collected for separate administrative purposes, rarely interoperable, and insufficiently transformed into operational decisions. This contrasts with the paradigm’s expectation that AIoT and cyber-physical systems should support real-time monitoring, predictive insight, and coordination across urban subsystems [24]. In this study, we assessed data-standard interoperability using a core set of indicators commonly used in digital-governance and ITS frameworks. These include: (i) the existence of unified data dictionaries for mobility indicators; (ii) standardized formats for fleet, route, and operational data; (iii) availability of real-time data streams and APIs; (iv) protocols for data sharing between operators and municipal authorities; and (v) mechanisms for integrating environmental, safety, and mobility datasets. The absence or fragmentation of these elements across the three cities served as evidence of limited interoperability and constrained analytical capacity.

The weakness is also institutional. Municipal authorities and operators appear to lack stable procedures for jointly defining data standards, maintaining shared databases, validating indicators, and converting evidence into iterative planning. Such limitations are especially consequential in intermediate cities, where constrained technical and financial resources coexist with informal mobility practices and rapidly changing travel patterns. Research on mid-sized cities similarly identifies limited institutional capacity, poor schedule

and route information, weak operational predictability, and insufficient data as recurrent barriers to sustainable bus-system development [1]. Consequently, digital applications introduced without institutional interoperability risk becoming isolated instruments rather than components of an integrated urban mobility architecture.

4.2.2. Environmental Sustainability

The second dimension is the gap between current mobility practices and the paradigm's environmental requirements. A smart and sustainable transport system must reduce dependence on fossil fuels, lower emissions and energy consumption, support active and collective modes, and strengthen resilience to climate and ecological pressures. In the three cities, however, environmental impacts are embedded in the modal and institutional structure of transport rather than generated by a small number of discrete sources.

Tunja's dependence on conventional collective transport and private vehicles is intensified by topographic conditions that make walking and cycling more difficult, while limited fleet transformation slows progress toward decarbonization. Barrancabermeja presents a distinct configuration in which industrial specialization, transport activity, informal competition, and environmental exposure interact. Industrial emissions and road traffic reinforce one another, while older and poorly regulated vehicles intensify local air-quality and safety pressures. Neiva combines an aging fossil-fuel-dependent collective fleet with a high prevalence of motorcycles, whose flexibility responds to weaknesses in formal transport but also generates emissions, noise, vulnerability, and road-safety risks. Heat exposure, peripheral road conditions, and limited shaded or protected infrastructure further show that environmental sustainability cannot be separated from climate-sensitive urban design.

Beyond modal composition and institutional constraints, technological improvements in vehicle propulsion, transmission, and structural components can also contribute to reducing fuel consumption and pollutant emissions in urban transport fleets. Recent studies show that smart mechanical innovations—such as optimized drivetrain elements and redesigned rear half-shaft assemblies in large urban transport vehicles—can enhance energy efficiency, reduce mechanical losses, and support ecological transition pathways even in contexts where full fleet electrification remains distant [46]. These incremental advances highlight that environmental sustainability depends not only on modal restructuring but also on the progressive integration of technological upgrades that mitigate the environmental burden of existing fossil-fuel-dependent fleets.

Across the three cities, electrification, clean-fuel transition, low-emission zones, protected cycling networks, and integrated active-mobility systems remain insufficiently demonstrated. The problem is therefore broader than fleet age or fuel type. Transport systems continue to reproduce a linear model in which energy-intensive vehicles move people through infrastructure not designed to minimize resource use, exposure, or environmental damage. This diverges from a paradigm based on decarbonized mobility, regenerative urban design, and coordinated resource management. Sustainable smart-city frameworks explicitly link technological innovation with reduced carbon emissions, improved energy efficiency, environmental resilience, and the social dimensions of sustainability; these objectives cannot be met when digital modernization is disconnected from modal restructuring and ecological performance.

4.2.3. Multimodal Integration

A third gap concerns the absence of a coherent multimodal system. The three cities display different modal configurations, but in each case the available modes operate more as parallel or competing alternatives than as coordinated components of a single

network. Tunja retains a relatively strong walking–collective-transport relationship, yet topography, discontinuous pedestrian infrastructure, and limited integration of cycling and bus services constrain its continuity. Barrancabermeja is characterized by the coexistence and competition of formal collective transport, informal services, motorcycles, and other flexible modes, with limited evidence of coordinated transfers or unified passenger information. Neiva is more strongly shaped by motorcycle dominance, which provides door-to-door flexibility but weakens the demand base and institutional centrality of collective transport.

These differences lead to a common structural outcome: passengers must assemble trips through personal knowledge, informal arrangements, and mode-specific choices rather than through an integrated mobility service. The evidence does not show comprehensive integrated ticketing, synchronized schedules, coordinated interchanges, unified route information, or a multimodal planning platform. The issue is not simply underdeveloped modes but weakly designed and institutionally unmanaged relationships among them. The paradigm instead requires seamless transitions, coordinated public transport, accessible active modes, and data-centric synchronization across infrastructure, vehicles, operators, and users. Digital twins and real-time analytics can support dynamic route, schedule, and resource adjustments in response to changing travel patterns [7], but such tools cannot compensate for the absence of basic institutional and physical integration.

4.2.4. Institutional Responsiveness and Governance

The fourth dimension is the gap between fragmented administration and responsive governance. In this paradigm, responsiveness does not mean merely reacting to complaints or implementing isolated projects; it implies the capacity to anticipate change, learn from operational feedback, coordinate across institutional boundaries, and revise policies through continuous interaction with citizens and system conditions. The three cities remain distant from this model because mobility responsibilities and resources are dispersed among municipal agencies, transport operators, informal providers, regional authorities, road-safety institutions, environmental agencies, and, in Barrancabermeja, industrial actors whose activities shape travel demand and environmental exposure.

This fragmentation weakens enforcement, obscures accountability, and limits the development of common priorities. In Tunja, physical and topographic constraints require coordination between land-use planning, pedestrian accessibility, public transport, and road management, yet the available response remains partial. In Barrancabermeja, formal regulation must contend with informal competition and industrial pressures that transport policy alone cannot manage. In Neiva, the municipality must address the interaction between dispersed urban growth, motorcycle dependence, peripheral accessibility, public transport modernization, and climate exposure, but the available evidence indicates insufficient coordination among the actors responsible for these domains. In all three cases, regulatory interventions have limited capacity to reshape entrenched mobility practices.

This governance gap prevents the iterative feedback loops that drive responsive cities. Citizen participation and local knowledge matter because residents can identify mobility needs that conventional indicators miss, especially when accessibility, safety, and service reliability vary across social groups. Nevertheless, participation requires institutional mechanisms that can incorporate this knowledge into budgeting, design, monitoring, and revision. Without those mechanisms, consultation may coexist with the same fragmented operational structure, producing responsiveness in discourse but not in system performance.

4.2.5. Social Equity and Accessibility

The fifth dimension is the unequal distribution of mobility opportunities and burdens. The smart, sustainable, and responsive city paradigm is not satisfied by technological efficiency if the resulting system excludes peripheral residents, increases exposure to pollution and traffic danger, or assumes that all users can choose among modes on equal terms. In Tunja, topography, uneven pedestrian infrastructure, and the spatial distribution of services shape walking and collective transport accessibility differently across the city. In Barrancabermeja, industrial activity, informal transport competition, environmental pressures, and service variability generate differentiated exposure and reliability. In Neiva, peripheral residents face the combined effects of dispersed urban form, heat, poor road conditions, limited shaded infrastructure, and dependence on motorcycles or older vehicles.

These conditions affect low-income households, informal workers, students, older adults, and people with disabilities in distinct but overlapping ways. The relevant burden is not limited to the fare: it also includes waiting time, transfer uncertainty, physical access to vehicles and stops, service availability outside peak periods, exposure to unsafe traffic and pollution, and the cost of reaching employment, education, healthcare, and essential services. Motorcycle use may reduce the immediate monetary and time costs of travel for households that can access a motorcycle, but it is not an equitable substitute for accessible collective transport and transfers risk to users who are often not able to absorb the consequences of injury, vehicle maintenance, or environmental exposure.

The evidence therefore suggests that modal dependence is shaped less by unconstrained preference than by socioeconomic position and the structure of available alternatives. This is incompatible with citizen-centered mobility, which requires inclusive access, participation, and the protection of vulnerable groups. The literature on responsive urban mobility likewise frames sustainability in relation to social inclusion, public health, air quality, energy consumption, and citizen participation rather than as a purely technical measure of network efficiency [47]. Recent studies also show that digitalization can reproduce or intensify existing inequalities when access to ICT-enabled mobility platforms is uneven: in Shenzhen, shared bicycle systems revealed that structurally vulnerable groups face greater barriers to accessing public transportation facilities and benefit less from smart mobility technologies [48]. Moreover, evidence from systematic reviews indicates that older adults and people with disabilities continue to face substantial accessibility barriers even as smart transport technologies advance, due to inadequate infrastructure, limited inclusive design, and challenges related to digital literacy and usability [49]. Environmental injustice and accessibility deficits thus become central indicators of the gap, not secondary social effects of transport planning.

5. Discussion

The central insight is that the divergence of Tunja, Barrancabermeja, and Neiva from the paradigm is systemic rather than incidental. The gap does not originate in any isolated deficiency—a shortage of vehicles, a single obsolete corridor, or the absence of a given digital application—but in the mutually reinforcing interaction of digital, environmental, multimodal, institutional, and equity-related constraints.

Limited data and analytical capacity restrict multimodal planning; fragmented modal structures perpetuate fossil-fuel dependence; and unequal accessibility reduces the system's ability to respond to heterogeneous social needs. This pattern aligns with the argument that smart mobility delivers its full value only when technologies and mobility solutions are embedded in interconnected ecosystems rather than deployed as stand-alone projects [3]. The three cities do not fail the mobility paradigm: residents move intensively, combining

walking, collective transport, motorcycles, and informal services. What is missing is a coordinated architecture that can turn these diverse practices into integrated, data-driven, and environmentally aligned networks.

This persistent gap reframes mobility transitions in intermediate cities. It reflects historical development trajectories—urban expansion, inherited layouts, and long-standing investment priorities—that produce transport structures resistant to isolated interventions. Planning remains reactive, and regulatory tools struggle to reshape entrenched practices, placing intermediate cities in a distinct structural position: informally adaptive yet lacking the integrated capacities the paradigm requires. Evidence from rapidly urbanizing contexts shows that smart-city trajectories are diverse and governance-dependent [11], and even flagship cases reveal that technological rollout often outpaces institutional responsiveness [19]. These transitions are therefore not technology-adoption problems but systemic reconfigurations in which infrastructure, institutions, and everyday mobility practices must evolve together.

The comparative design shows that shared structural constraints materialize differently in each city, and this differentiation is analytically significant. In Tunja, topography and a strong walking-and-collective-transport culture channel the gap toward physical accessibility, network continuity, and partial digital integration. In Barrancabermeja, industrial specialization, informal competition, and environmental pressures generate safety burdens and a marked data-governance deficit. In Neiva, dispersed form, heat, and motorcycle dominance produce individualized flexibility that compensates for weak collective coordination while reinforcing emissions and peripheral exclusion; limited air-quality monitoring underscores constrained analytical capacity. These are distinct expressions of a common systemic condition, consistent with evidence that spatial and temporal disparities obstruct integrated and equitable transport systems even in high-capacity contexts [30]. The paradigm is therefore not approached from a uniform baseline: historical form, economic specialization, modal cultures, and institutional capacity determine how each city diverges from it.

The empirical evidence also refines the conceptual paradigm, challenging three implicit assumptions. Digital readiness is not equivalent to smartness: in Tunja, GPS and passenger-counting support monitoring but do not form a user-oriented ITS, and in Barrancabermeja, real-time location, electronic payment, and central monitoring remain future recommendations rather than operational capabilities—echoing critiques that “smartness” becomes an empty signifier when innovation does not translate into inclusive civic life [19]. Sustainability cannot be reduced to fleet technology, since environmental impacts are embedded in modal and institutional structures. Responsiveness is a governance capacity, not a participatory discourse: consultation mechanisms paired with fragmented operations generate rhetorical rather than functional responsiveness. Digital tools deliver value only through ecosystem-level coordination among institutions, technologies, and stakeholders [13], and assumptions of uniform scalability or transferable policy templates are untenable in resource-constrained settings [11,19].

The cases further expose tensions within the paradigm that its idealized formulation rarely acknowledges. Digitalization can conflict with environmental sustainability, since the widespread adoption of smart technologies—IoT sensors, data centers, urban management platforms, and 5G networks—demands energy-intensive infrastructure that still relies heavily on fossil fuels. It can also conflict with responsiveness, as digital engagement reproduces exclusion when digital literacy, privacy concerns, and motivational access are uneven. International evidence illustrates this pattern: in Chengdu, for example, 60% of elderly residents avoid digital platforms because of surveillance concerns, and participation rates reach 75% among higher-income groups versus 45% among low-income residents [8].

The three axes of the paradigm therefore do not automatically align; intermediate cities must negotiate explicit trade-offs—sequencing digital investment, environmental modernization, and inclusive participation—rather than assume their convergence [8,19].

These interpretive insights should be understood in light of the study's methodological constraints. The analysis relies on secondary indicators with heterogeneous measurement years, uneven coverage of informal transport, and varying levels of operational detail across municipal sources. As a result, the associations identified between modal structures, institutional conditions, environmental pressures, and accessibility outcomes should be interpreted as structural co-occurrences rather than causal mechanisms. The three cases illustrate context-specific expressions of shared constraints, but they do not statistically generalize to all intermediate cities.

For medium-sized cities with limited resources, prioritizing digitalization, environmental protection, and public participation requires a sequenced, context-sensitive approach. Digitalization should begin with foundational data-governance practices—such as unified data dictionaries, interoperable formats, and basic real-time monitoring—rather than high-end AIoT deployments. Environmental protection should focus on low-cost, high-impact interventions such as fleet renewal, active-mobility continuity, and monitoring emissions. Public participation must be embedded early to ensure digital and environmental measures respond to lived mobility needs and do not exacerbate inequities. This layered prioritization allows cities to build institutional maturity while progressively aligning with the smart, sustainable, and responsive paradigm.

The theoretical and practical implications follow directly from this refinement. Technocentric approaches have clear limits: electrification without integrated operations may replace vehicles without improving accessibility; digitalization without data governance may deepen fragmentation; and infrastructure expansion without social and environmental criteria may reproduce exclusion. Documented barriers—interoperability concerns, privacy risks, regulatory lag, and infrastructure costs—further constrain smart-mobility adoption [3]. Digital tools generate value only when embedded in integrated governance arrangements with shared data standards, common databases, validated indicators, and iterative planning. They must also align with institutional capacity and lived mobility realities, since accessibility, safety, and reliability vary across social groups in ways conventional indicators miss, and assessment frameworks should rest on transparency, non-exclusion, equity, and responsiveness, advancing toward decision-making and co-management levels [47]. Investments must therefore match spending on sensors, platforms, and clean technologies with the administrative capacity required to operate and govern these systems effectively [29].

The equity analysis identifies the most binding constraint on smart and sustainable transitions. The relevant burden extends beyond fares to waiting time, transfer uncertainty, physical access, off-peak availability, exposure to unsafe traffic and pollution, and the cost of reaching employment, education, healthcare, and essential services. Transport expenditure approaching a quarter of low-income household budgets in Barrancabermeja shows that nominal affordability does not ensure equitable accessibility. Motorcycle use may reduce immediate travel costs for those who can access one. Still, it shifts injury, maintenance, and environmental risks onto users with unequal capacities to absorb them and excludes those who cannot drive. Patterns of modal use respond less to autonomous choice than to socioeconomic position and the limited range of feasible alternatives within the system. These findings align with evidence that vulnerable groups (older adults, people with disabilities, and low-income residents) are often marginalized in access to smart mobility services [19]. Inclusive ITS remain uneven, with fragmented policies, inconsistent accessibility standards, and underrepresentation of developing regions [4]. Environmental

injustice and accessibility deficits are thus central indicators of the gap; transitions that assume equal modal choice or prioritize technological efficiency over inclusive access risk deepening the exclusion they aim to address.

Policy implications point to five priorities for intermediate cities. First, data systems: continuous, interoperable, high-resolution information is essential for coordinated planning and reliable passenger information. Second, multimodal coordination: integrated fares, synchronized schedules, interchange facilities, and unified passenger information form the operational core of integrated networks, as shown by mass-transit strategies with real-time information and unified journey planning [33], and by evidence that connectivity gaps restrict access to employment and essential services [30]. Third, fleet modernization: multi-objective planning shows that route and fleet decisions can reduce emissions without sacrificing efficiency [7].

Recent evidence also shows that fleet modernization benefits from structured decision-support tools capable of integrating environmental, operational, and long-term sustainability criteria. Conventional procurement processes often prioritize short-term financial considerations, limiting the potential for ecological transition. Fuzzy-based decision systems—such as those applied to transport equipment selection in green port operations—demonstrate how multidimensional sustainability indicators, including emissions performance, energy efficiency, operational reliability, and lifecycle impacts, can be incorporated into equipment selection processes [50]. These approaches illustrate how municipalities could adopt more robust analytical tools to align fleet renewal with broader sustainability objectives, ensuring that technological upgrades contribute to systemic environmental improvements rather than isolated technical gains.

Fourth, governance integration: coordination across municipal authorities, formal and informal operators, and regional actors enables every other front, and informal modes should be incorporated into regulated integration rather than excluded [4]. In medium-sized cities, regulating and integrating informal transport requires a phased, pragmatic approach. A first step is to formalize basic operational information—routes, schedules, fleet characteristics, and safety records—through low-cost registration mechanisms. The second step is to create transitional regulatory instruments that allow informal operators to enter hybrid schemes, such as semi-formal service contracts or community-based concessions. A third step involves integrating these services into municipal planning through unified route maps, interoperable fare systems, and shared digital reporting tools. Finally, cities should establish incentive-based compliance mechanisms—such as access to credit for fleet renewal or priority corridor allocation—to ensure that integration improves service quality without displacing vulnerable operators. This sequence provides a realistic pathway for cities with limited institutional capacity to progressively align informal transport with formal mobility governance.

Fifth, climate-sensitive design: active-mobility networks, shading, drainage, and peripheral infrastructure are central to sustainable, non-automobile urban form. Incremental improvements to routes, fleets, or platforms cannot close a gap shaped by urban form, governance, modal dependence, and unequal resources; a system-level transition linking real-time knowledge, decarbonization, multimodal integration, adaptive governance, and equitable access is required.

The study also offers a framework whose relevance extends beyond the three cases. By showing how territorial and socioeconomic contexts channel shared structural constraints, the analytical lens—digital capacity, environmental performance, multimodal integration, institutional responsiveness, and social equity—provides a comparative reference for evaluating mobility transitions in other intermediate cities. Future research should adopt integrated, data-driven, multimodal, and equity-oriented approaches that link operational

performance with spatial access, environmental exposure, institutional responsiveness, and lived experience. Emerging modeling tools designed for data-scarce and fragmented contexts offer promising pathways for advancing this agenda [6].

6. Conclusions

This article identifies a systemic gap between the smart, sustainable, and responsive mobility paradigm and the realities of Tunja, Barrancabermeja, and Neiva. Rather than demonstrating causal mechanisms, the analysis reveals recurrent associations between limited analytical capacity, environmental pressures, fragmented modal structures, institutional weakness, and unequal access. These co-occurring conditions leave digitalization partial and technologies isolated rather than integrated. Each city expresses this configuration differently—Tunja through topography and reliance on walking and collective transport, Barrancabermeja through industrial specialization and informal competition, and Neiva through motorcycle-based individualized flexibility—showing that the paradigm is not approached from a uniform baseline. Recurring incomplete data systems, fossil-fuel dependence, fragmented governance, and unequal access suggest a broader pattern across intermediate cities. These burdens fall disproportionately on peripheral and low-income households, students, older adults, and people with disabilities, underscoring that accessibility is inseparable from environmental justice and should be assessed across social, economic, environmental, planning, governance, and participation dimensions rather than through network efficiency alone [47].

Because these patterns are embedded in broader systems of urban development and governance, isolated improvements to vehicles, routes, platforms, or infrastructure are unlikely to address them fully. Instead, the evidence points to the need for a system-level transition that links real-time knowledge, decarbonization, multimodal integration, adaptive governance, and equitable access through a common strategy. The article provides an empirical baseline and an interpretive framework for assessing whether future changes produce genuinely smart, sustainable, and responsive systems or merely technical upgrades. Future research should adopt integrated, data-driven, multimodal, and equity-oriented approaches that relate performance to access, exposure, institutional responsiveness, and lived experience.

For Colombian intermediate cities, addressing this misalignment is urgent because continued fragmentation is consistently associated with environmental harm, unequal access, institutional weakness, and dependence on precarious individual solutions. The study's enduring contribution is to make the systemic character of the gap visible and to establish its closure as a central question for mobility research in intermediate cities.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
IoT	Internet of Things
AIoT	Artificial Intelligence of Things
CO ₂	Carbon Dioxide
CPS	Cyber-Physical Systems
Db	Decibel
GPS	Global Positioning System
ICT	Information and Communication Technologies
ITS	Intelligent Transportation Systems

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