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Article

Mapping the Barriers to Smart Mobility Adoption: A Multi-Criteria Analysis Using TISM-MICMAC

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Highlights

Despite extensive research on barriers to smart mobility, prior studies have largely treated them in isolation, overlooking their systemic interconnections and root causes. This study employs Total Interpretive Structural Modelling (TISM) and MICMAC analysis, underpinned by Critical Urban Theory, to structurally map and interpret the interrelationships among the barriers.

What are the main findings?

- Legacy paradigms in conventional transport planning, fragmented mandates, and outdated regulations emerge as root causes of resistance to smart mobility.
- User-related issues such as affordability, spatial coverage, and cultural attachment to cars are dependent barriers, shaped by upstream institutional and governance failures.

What is the implication of the main finding?

- Tackling smart mobility challenges requires structural reforms that dismantle entrenched planning logics and improve cross-institutional coordination.
- Policymakers and planners, particularly in the Global South, should prioritize high-driving-power barriers to unlock cascading benefits across the mobility system.

Abstract

Smart mobility is widely promoted as a solution to the urban challenges of congestion, pollution, and inefficient transportation systems. Yet, its adoption remains inconsistent, particularly in developing cities where structural and systemic barriers are dominant. Prior research has examined enabling factors such as digital infrastructure and user perceptions, but has paid limited attention to the institutional, political, and socio-cultural constraints that influence adoption. Moreover, whenever considered, the barriers are studied in isolation, obscuring their systemic interactions. This study addresses this gap using Total Interpretive Structural Modelling (TISM) to hierarchically map the barriers. To complement the analysis, MICMAC classification is used to assess their driving and dependence power. Findings reveal that legacy paradigms in conventional transport planning, fragmented institutional mandates, and regulatory misalignment are the foundational barriers, reinforcing downstream challenges such as affordability constraints, limited service coverage, and persistent car-centric preferences. Anchored in Critical Urban Theory, the study depicts how smart mobility adoption is not a neutral technological process, but one deeply embedded in wider struggles over governance, equity, and urban development. The paper contributes to the literature by offering a theory-building framework that captures the interdependence of institutional, technological, and behavioral barriers. It also provides practical entry points for policymakers, planners, and mobility innovators seeking to target root cause interventions rather than symptoms, thereby enabling more equitable, scalable, and resilient smart mobility transitions.

Keywords: smart mobility; barriers to adoption; critical urban theory; Total Interpretive Structural Modelling (TISM); MICMAC analysis; emerging cities

1. Introduction

Cities worldwide are under mounting pressure to transform their transport systems in response to rapid urbanization, climate imperatives, and digital innovation. In this context, smart mobility, which entails the integration of digital technologies, multi-modal transport options, and user-centered services, has emerged as a potential solution to longstanding urban mobility challenges [1,2]. Defined as the application of technology and data to create efficient, sustainable, and user-friendly transport systems, smart mobility promises to optimize efficiency, reduce environmental impacts, and enhance urban livability [3–6].

Yet, despite its transformative potential, the adoption of smart mobility is inconsistent, particularly in cities of the Global South. Existing research has largely focused on enabling factors such as service efficiency, digital infrastructure and perceived usefulness [7–9], but offers limited insight into how barriers may impede adoption. Furthermore, studies on barriers have explored them in isolation, overlooking the systemic interactions between institutional inertia, governance fragmentation, regulatory constraints, and social resistance [10,11]. As a result, little is known about the relative power and influence of these barriers, or which among them function as root causes of resistance to smart mobility transitions. A central but underexplored barrier lies in the legacy paradigms of conventional transport planning (CTP). Rooted in rational-comprehensive and car-centric models, CTP prioritizes traffic flow, vehicle throughput and saving time over flexibility, accessibility and multimodal integration [12,13]. Such paradigms are fundamentally misaligned with the adaptive, data-driven, and user-centered logics of smart mobility [14,15]. This institutional misfit is further compounded by fragmented mandates across transport agencies, outdated policies, gaps in digital literacy, and uneven infrastructure that create a web of resistance to mobility innovation [16,17].

This paper addresses these gaps by moving beyond descriptive accounts to offer a systems-level and theory-informed analysis of barriers to smart mobility adoption. Drawing on Critical Urban Theory, the study interrogates the political, economic, and ideological forces shaping mobility transitions, thereby responding to recent calls for more socially attuned mobility research [18]. In doing so, the study positions smart mobility adoption not as a neutral technological project, but as a contested process embedded within wider struggles over urban governance, equity, and sustainability.

The findings reveal that legacy paradigms in transport planning, fragmented mandates, and regulatory misalignment function as root causes exerting a strong influence, shaping downstream challenges such as affordability, spatial coverage, and cultural attachment to car ownership. This finding signals that resistance to smart mobility adoption emerges not from isolated technical deficits, but from an interconnected ecosystem of institutional, political, and socio-cultural constraints.

By combining Critical Urban Theory with structural modelling methods, this study contributes to the growing literature on urban mobility transitions in three ways. First, it advances a holistic framework that identifies and maps how barriers interact. Second, it reframes adoption challenges as products of institutional and political dynamics, challenging the prevailing technocratic narratives of smart mobility. Third, it offers practical entry points for policymakers to target structural root causes, with particular relevance for Global South cities seeking to develop inclusive, scalable, and resilient smart mobility systems.

The remainder of the paper is structured as follows. Section 2 reviews the theoretical and empirical literature on smart mobility barriers. Section 3 outlines the research methodology. Section 4 presents the results of the TISM and MICMAC analyses. Section 5 discusses the implications of the findings, and Section 6 concludes with recommendations for policy, practice, and future research.

2. Theoretical Background: Smart Mobility Adoption Barriers

2.1. Framing Smart Mobility in Urban Sustainability Discourse

Smart mobility has emerged as a paradigm shift in urban transport, promising enhanced efficiency, reduced environmental impact, and increased accessibility through the integration of digital technologies, data-driven services, and platform-based transport innovations. Built on digital platforms, algorithmic optimization, and real-time data exchange, smart mobility is recognized for its transformative potential through technologies such as AI-enabled traffic control, Mobility-as-a-Service (MaaS), micro-mobility, and automated vehicles [19,20]. In both policy and academic discourse, these technologies are framed as offering efficient, low-emission, and user-centric transport alternatives [1].

However, beneath these aspirations lie a web of institutional, technological, and social tensions that challenge the actualization of smart mobility at scale. Moreover, critiques have emerged that challenge the techno-optimistic framing of smart mobility [21]. Scholars have highlighted the risk of "solutionism", where digital tools are seen as ends in themselves rather than parts of broader systemic change [22,23]. Additionally, these solutions have raised concerns about equity, privacy, data governance, sustainability and urban exclusion [24]. Concerns have been raised about the social, political, and ethical dimensions, especially the issues of data governance, surveillance, spatial exclusion, and the reinforcement of inequality, which could hinder smart mobility adoption [10,25,26]. Overall, these critiques suggest that the success of smart mobility cannot be measured solely by technological efficiency or emissions reductions, but must also consider how power, access, and other barriers are distributed in its implementation.

2.2. Barriers to Smart Mobility Adoption

Despite the increasing promotion of smart mobility as a sustainable and efficient alternative to traditional transport systems, its widespread adoption remains uneven across cities, especially in developing urban contexts. A growing body of literature has examined various barriers impeding smart mobility adoption, yet most studies tend to address these challenges in isolation. Drawing on behavioral, institutional, and technological theories, this section provides a review of key barriers identified in this study.

2.2.1. Interoperability and Integration Deficits

A lack of interoperability among different transport services and poor integration of payment systems, real-time information, and routing functionalities diminish the user experience [27]. The absence of common standards, data interoperability protocols, and coordinated system architectures makes the integration of various mobility services difficult. Interoperability can, however, be enhanced through open standards, shared platforms, and public-private partnerships [28].

2.2.2. Inadequate Digital Infrastructure

The success of smart mobility is contingent on robust digital infrastructure, including high-speed internet, GPS coverage, and IoT-enabled systems [26]. It is equally important to have an elaborate infrastructure to collect, organize, access and control data. In cities or areas where these are lacking or unreliable, deployment is delayed or limited in scope [29]. Smart mobility is predicated on digital access, literacy, and engagement. Yet, significant segments of the population remain digitally excluded due to lack of smartphone access, limited digital literacy, or affordability issues. This digital divide has been found to disproportionately affect low-income, elderly, and marginalized urban residents, signaling that smart mobility could exacerbate mobility injustice rather than alleviate it [30–32]. However, targeted investments in digital infrastructure can act as enablers, particularly when aligned with national digital transformation agendas [33].

2.2.3. Data Privacy and Security Concerns

Smart mobility systems rely heavily on data collection, processing, and sharing. Privacy concerns and lack of robust data protection frameworks undermine user trust and hinder uptake [34–37]. Studies have pointed out the growing power asymmetries between private mobility platform providers and users, particularly when data is collected and monetized without sufficient transparency or regulation [24,38]. From a socio-technical perspective, perceived surveillance and loss of control over personal data reduce willingness to adopt [39]. Conversely, transparent data governance and ethical design practices can enhance trust and system acceptance [40].

2.2.4. Inclusive Design Deficiencies

Smart mobility systems may fail to meet the needs of persons with disabilities, older adults, and those with caregiving responsibilities [41–43]. Further, smart mobility systems use algorithms such as dynamic pricing, route allocation, or predictive policing, which can inadvertently reinforce social inequalities or spatial exclusion [44]. For instance, ride-hailing algorithms may prioritize profitable zones over underserved areas, or price surges may penalize those with limited transport alternatives [45]. Digital and physical exclusion results whenever universal design principles are not integrated into mobility innovations. Conversely, inclusive design can significantly broaden user adoption and enhance societal benefits [46].

2.2.5. Fragmented Institutional Mandates

The governance of urban transport involves multiple institutions with overlapping or poorly defined mandates, leading to inefficiencies, conflicting policies, and lack of coordination [47,48]. Fragmentation hinders smart mobility by stalling integrated planning and the deployment of multimodal systems. On the other hand, governance integration and inter-agency collaboration have been shown to enhance coordination and streamline innovation diffusion [16,49].

2.2.6. Unsupportive Regulations and Policies

Outdated or misaligned transport regulations can obstruct smart mobility by failing to accommodate emerging models such as micromobility, shared services, or Mobility-as-a-Service (MaaS) [50]. Likewise, regulatory uncertainty deters private investment and experimentation [51]. Yet, enabling policies such as incentives, open data frameworks, and supportive licensing regimes have demonstrated success in accelerating adoption in cities like Helsinki and Singapore [52].

2.2.7. Legacy Paradigms in Conventional Transport Planning (CTP)

Conventional transport planning (CTP) frameworks, rooted in mid-20th-century planning logics, continue to pose significant obstacles to the adoption of smart mobility. Traditionally centered around car-oriented development, CTP prioritizes infrastructure investments in road networks, emphasizes traffic flow and vehicle throughput, while marginalizing investments in public and non-motorized transport [53,54]. These practices contribute to spatial inequities and reinforce auto-dependence, particularly in urban peripheries.

Institutional inertia and sunk costs in legacy infrastructure further entrench these paradigms, creating path dependencies that stifle innovation [55]. Planning remains largely governed by rational-comprehensive approaches that rely on predictive models and outdated indicators such as congestion levels and travel times [14,56]. These models are poorly equipped to address contemporary challenges such as digital disruption, the unpredictability of travel behavior, and the urgency of decarbonizing transport systems [57].

While CTP and smart mobility share some overlapping goals, such as emissions reduction and modal shift, they differ fundamentally in approach and evaluative capacity. CTP lacks the frameworks necessary to regulate or integrate innovations like Mobility-as-a-Service (MaaS), micromobility, or real-time data-driven services [15]. In contrast, smart mobility emphasizes adaptability, user-centered design, digital integration, and resilience [3]. Yet, smart mobility is not without

contradictions: while it promises quality-of-life improvements and greater system efficiency [5,58], it may inadvertently lead to longer trip distances and higher vehicle miles traveled (VMT), potentially undermining the compact urban development and reduced travel demand that CTP has historically pursued [59,60]. This apparent conflict highlights a deeper paradigmatic misalignment between legacy planning institutions and the techno-urban logic underpinning smart mobility [17]. The resulting tension limits the capacity of cities to pursue integrated and future-ready transport solutions. Scholars have increasingly called for a paradigm shift—away from rigid, automobile-centric models—toward participatory, flexible, and sustainability-oriented planning [14,61].

Without redefining institutional priorities, updating planning tools, and adopting new evaluative metrics, smart mobility risks being co-opted by outdated systems that fail to deliver on its promise. This study therefore recognizes legacy CTP not as a neutral backdrop, but as an active, structural barrier influencing the governance, adoption, and long-term effectiveness of smart, sustainable, and resilient mobility systems [16,59].

2.2.8. Political Resistance

The politics of urban mobility typically reflects entrenched interests and ideologies. Resistance can stem from political actors reluctant to disrupt existing systems, fear of backlash from powerful car lobbies, or lack of political will to promote transformative policies [62]. However, political leadership and narrative framing can play a transformative role, particularly when smart mobility is positioned within broader goals of equity, climate action, and economic resilience [31].

2.2.9. Digital Literacy Gaps

Low levels of digital literacy, particularly among older adults, low-income groups, and marginalized communities, would hinder the equitable adoption of app-based smart mobility services [63]. According to the digital divide theory, unequal access to digital skills reproduces mobility and social exclusion [64]. Certain approaches to address these gaps have been suggested namely user training, multilingual interfaces, and co-design approaches that reflect user diversity [65].

2.2.10. Safety Concerns for Pedestrians and Cyclists

Smart mobility solutions are defined by walking and cycling as key components of sustainable transport. Yet, inadequate infrastructure, poor lighting, and unsafe road conditions deter use, especially among vulnerable groups [66]. Safety improvements not only enable greater uptake of active modes but also increase public confidence in multimodal travel options [67].

2.2.11. Public Transport Appeal

Smart mobility is most effective when integrated with high-quality public transport. However, in many urban contexts especially in the developing cities, public transport suffers from unreliability, overcrowding, and negative public perceptions [68,69]. Enhancing service quality and branding public transit as a premium, sustainable choice can reposition it as a desirable option within smart mobility ecosystems.

2.2.12. Limited Coverage of Smart Mobility Services

Smart mobility services in developing megalopolis are mainly concentrated in central urban areas, neglecting peri-urban and other underserved communities. This spatial bias limits access and reinforces inequality [70]. To bridge this gap, it has been suggested to expand coverage through geographic subsidies, demand-responsive transport and spatial equity policies [13,71].

2.2.13. Affordability of Smart Mobility Options

Cost remains a critical barrier, especially for lower-income groups. Despite the promise of shared mobility to lower costs, pricing models can remain prohibitive [72]. Flexible fare structures, subsidies, and bundling services for options like MaaS schemes can make smart mobility more affordable [73].

2.2.14. Car as a Status Symbol and Personal Space

Automobile ownership is deeply embedded in cultural and social norms, which to some degree symbolize success, freedom, and identity [74]. This psychological barrier can impede modal shift to shared and collective modes. While, it is apparent that generational change, climate awareness, and urban lifestyle shifts are slowly eroding this status quo, the affection for cars is enduring [12].

2.3. Critical Theory and Smart Urbanism

The rise of smart mobility cannot be fully understood through technological or functionalist lenses alone. Instead, its evolution and adoption must be situated within broader political, institutional, and ideological contexts [18]. Critical Urban Theory, rooted in neo-Marxist and post-structuralist traditions, provides an essential lens for interrogating how power, inequality, and ideology are embedded within the technological transformation of cities [75]. From this perspective, smart urbanism, and by extension, smart mobility, is not a neutral or universally beneficial innovation but a politically charged project that reflects and reproduces dominant interests [24,76].

At its core, critical theory challenges the instrumental rationality that underpins many smart city initiatives, including transport innovations. It critiques the “techno-solutionism” embedded in smart mobility discourse; the idea that digital technologies alone can resolve prevailing urban problems such as congestion, pollution, or inequity. Instead, critical theorists argue that such solutions often obscure underlying structural issues and depoliticize urban governance by shifting attention away from social justice, redistribution, and institutional accountability [77].

In the context of smart mobility, this critique is particularly salient. Technologies such as ride-hailing, Mobility-as-a-Service (MaaS), autonomous vehicles, and AI-based traffic systems have been introduced without sufficient attention to who benefits, who governs, and who is excluded. Therefore, smart mobility platforms frequently reproduce spatial, economic, and digital inequalities, privileging affluent users and well-served urban cores while marginalizing peripheral communities [30,38]. Furthermore, the privatization of data infrastructures and the influence of large tech firms in shaping urban transport agendas raise questions about democratic oversight, transparency and citizen agency.

More importantly, critical theory foregrounds the role of institutional path dependencies and systemic inertia, which are key concerns in this study. The adoption of smart mobility does not occur in a vacuum; it is filtered through existing urban governance systems, including Conventional Transport Planning (CTP) frameworks, which have long prioritized automobility, infrastructure expansion, and predictive forecasting models. These legacy systems can subtly constrain or redirect smart mobility in ways that reinforce established priorities and resist transformative change. As such, the conflict between CTP and smart mobility is not just technical or procedural, as it reflects a deeper ideological clash between rational-comprehensive planning models and more emergent, data-driven, and user-centric logics.

Moreover, critical theory allows us to see CTP as a site of epistemic power, where certain forms of knowledge (e.g., traffic modeling, vehicle throughput metrics) are privileged over others (e.g., lived experience, community-based mobility practices and quality of life). This epistemic hierarchy contributes to the marginalization of alternative mobility visions, such as feminist, de-colonial, or sustainability-oriented transport paradigms [31].

Through the critical theory lens, this study interrogates not just the visible barriers to smart mobility adoption, such as digital access or institutional silos, but also the invisible logics, inherited paradigms, and institutional configurations that structure how urban mobility is imagined, governed, and enacted. It helps uncover how legacy planning systems may constrain innovation not by design, but by habit, ideology, or governance inertia. By so doing, critical theory reframes smart

mobility adoption as a contested and political process, shaped by entrenched institutional logics, uneven power relations, and conflicting urban imaginaries [18]. It offers a valuable framework for analyzing how emerging technologies interact with and are constrained by legacy systems like CTP, thereby enriching our understanding of why smart mobility adoption remains partial, uneven, and fraught with contradictions.

3. Materials and Methods

This study adopts Total Interpretive Structural Modelling (TISM) to identify and analyze the key barriers that hinder smart mobility adoption in urban settings. Specifically, the research combines a mini literature review to establish a list of potential barriers and then examines their interrelationships using expert consultation. The role of experts was to aid in distilling the list of barriers, analyzing the correlation among barriers, and providing the interpretive logic [78]. This approach is particularly suitable due to the dual nature of the study objectives: (i) exploring the range of obstacles to smart mobility uptake and (ii) establishing structured relationships of how these barriers reinforce or interact with one another.

3.1. Identification of Barriers

This study began with a literature review to extract potential barriers to the adoption of smart mobility. Drawing from over 10 peer-reviewed articles, policy reports, and systematic reviews, a total of 31 barriers were identified (see Table 1). The original list drew from various interdisciplinary sources across transport planning, urban studies, technology adoption, and public policy [2,8,9]. These barriers captured a wide range of institutional, technological, behavioral, and infrastructural constraints. A summary of the original barriers and their sources is presented in Table 1.

Table 1. Original List of Barriers to Smart Mobility Adoption obtained from literature review.

No.	Barrier	Source
1	Infrastructure for sustainable mobility	[27,79]
2	Openness to Innovation and new technologies in mobility	[27,80,81]
3	Platform security	[27,32]
4	Public transport attitude	[81–83]
5	Car-dependency reduction	[84]
6	Conventional Transport Planning (CTP)	[15,59,84]
7	App-based (on-demand) mobility services	[15]
8	Active mobility	[15]
9	Basic transportation access	[32,85]
10	Access to data and the internet	[32]
11	Digital and banking divide	[27]
12	Low digital literacy and privacy concerns	[32,86]
13	Perceived security	[86,87]
14	Conservative mindsets and customer acceptance	[83,87]
15	Data safety, ethics, and surveillance concerns	[11]
16	Regulatory and legal uncertainty (liability, insurance)	[83,87,88]
17	Urban-centric service coverage	[87]
18	Lobbyism and industry influence	[87]
19	Loss of car as personal space/status symbol	[81,87]
20	Public acceptance of shared mobility	[83]
21	Legislation, taxation, and funding gaps	[88]
22	Weak business models and market uncertainty	[88]
23	Lack of cooperation among stakeholders	[88]
24	Interoperability and multimodal coordination issues	[10,27,89]
25	Ticketing/payment system fragmentation	[89]
26	Weak integration with public transport in underserved areas	[10,90]
27	Tradition of private vehicle ownership	[79,81]
28	Limited platform appeal to older adults and conservative users	[79]
29	Fragmented vision, collaboration, and data-sharing	[79,91]
30	Financial/resource constraints	[91]

The list reflected a wide range of conceptual overlaps and varying levels of abstraction; thus, it was necessary to streamline the barriers to facilitate effective modeling and interpretation. To make the subsequent structural modelling tractable and meaningful, it was necessary to refine and consolidate the list. First, duplicate or overlapping barriers were merged. For instance, “access to data and internet,” “digital and banking divide,” and “lack of knowledge about smartphones and internet” were conceptually aggregated under broader categories such as digital literacy gaps or inadequate digital infrastructure [94]. Similarly, multiple entries relating to the socio-cultural role of car ownership (e.g., loss of car as a status symbol, as personal space, and the tradition of private vehicles) were consolidated into a unified barrier representing the psychosocial attachment to private cars.

Following this conceptual distillation, a focus group discussion was conducted with five domain experts drawn from Nairobi, Kenya’s commercial and transportation hub. The experts who comprised an urban transport planner, policy analyst, academic, and digital mobility practitioner were convened to further validate and streamline the list. This step was necessary to assess the face validity and contextual relevance [95,96]. Drawing on the principles of the Delphi method [97], the experts were organized into a focus group that engaged in iterative discussions to ensure the consistency, contextual relevance, and non-redundancy of the identified barriers [97]. The experts assessed each item based on its systemic influence, relevance to the study objectives, and potential for policy intervention.

In parallel, a theoretical filtering process ensured that the retained barriers aligned with the study’s aims and were analytically suitable for the Total Interpretive Structural Modeling (TISM) framework [78]. Barriers that were too broad to allow precise pairwise comparison or lacked sufficient interpretability (e.g., “smart leadership”) were deemed unsuitable for interpretive modeling. Only those barriers that were specific, actionable, and theoretically grounded yet broad enough to capture systemic dynamics were retained. The expert-driven reduction aligns with prior studies that have emphasized the importance of domain-specific filtering in interpretive modelling exercises [78,98]. Finally, the process narrowed the original list down to 14 barriers, which were deemed to be the most salient, structurally relevant, and theoretically significant for the study context. These 14 barriers, presented in Table 2, served as the input variables for the Total Interpretive Structural Modelling (TISM) and MICMAC analysis conducted in subsequent sections.

3.2. Research Approach

The research is situated within an interpretivist paradigm, which supports the co-construction of meaning through the subjective interpretation of expert insights and existing literature. Thus, an inductive approach was used that enabled the emergence of key themes from data and structured theory building. An inductive approach enabled the derivation of the list of barriers through literature synthesis and expert validation. Subsequently, relationships among these barriers were mapped and modeled using TISM.

3.3. The Choice of Total Interpretive Structural Modelling (TISM) in this Study

The core objective of this study is twofold: first, to identify the key barriers that hinder the adoption of smart mobility in urban contexts, and second, to analyze how these barriers interact to reinforce or impede adoption. This dual aim, which is both diagnostic and explanatory, requires a methodological approach that can reveal not only the existence of barriers but also their structural interdependencies and relative influence.

Total Interpretive Structural Modelling (TISM) was selected as the principal analytical technique because it is well-suited for theory-building in complex, underexplored domains. Smart mobility adoption, especially in developing urban contexts, is characterized by multilayered challenges spanning technological, institutional, and behavioral dimensions. While the field has seen growing

interest in recent years, mass adoption has been hindered due to persistent barriers that limit system scalability [2]. There is a dearth of research that has systematically analysed the barriers using a structured methodology that moves beyond simple identification toward a layered interpretation of how they interconnect and evolve over time.

TISM is an advanced extension of the Interpretive Structural Modelling (ISM) method [99–101] enriched by the incorporation of interpretive logic. Unlike ISM that identifies binary relationships between factors, TISM advances this by requiring justifications for why and how specific relationships exist [78,102,103]. This interpretive depth enables researchers to build more meaningful, actionable models relevant for policy makers who, need to understand systemic resistance in order to design effective interventions.

Following a literature review and expert consultations, this study identified a preliminary set of barriers operating across three levels: user-related (e.g., behavioral inertia, low digital literacy), technological (e.g., limited interoperability, inadequate infrastructure), and institutional (e.g., regulatory fragmentation, lack of policy coordination). TISM was then employed to model how these barriers interact, resulting in a structured hierarchy that distinguishes between driving barriers (those that initiate or intensify other challenges) and dependent barriers, (which manifest as downstream symptoms of broader systemic issues). This approach allows the study to address the core dimensions of theory development articulated by [104]. By so doing, the model not only identifies which barriers are most critical, but also explains how they reinforce or amplify one another and why they deserve priority attention in policy or planning.

Recent methodological enhancements in TISM, such as the integration of argumentation-based reasoning [105], were integrated in the interpretative logic to further strengthen the model's validity. This extension allows the relationships between elements to be grounded not just in observation or consensus, but also in stakeholder justification. This is particularly relevant for smart mobility systems, which evolve and require different policy responses at different stages from initiation, scaling, through to stabilization. TISM's flexibility makes it possible to identify which barriers are most salient at each of these stages, offering a dynamic and context-sensitive roadmap for intervention.

3.4. Justification for TISM over Alternative Methods

To ensure methodological rigor, TISM was evaluated against alternative multi-criteria decision-making and systems modeling techniques, including Interpretive Structural Modelling (ISM), Analytic Hierarchy Process (AHP), and DEMATEL. While ISM is widely used to identify and structure key elements within complex systems [106,107], providing clarity by establishing relationships among these elements [108], it does not allow for interpretive elaboration, fails to include transitive links, and hence limits its explanatory power [109]. On the other hand, AHP, though useful for prioritizing factors, is more suited to quantitative comparisons and lacks the ability to map causal relationships or generate hierarchical models based on qualitative inputs [110]. Similarly, Decision-Making Trial and Evaluation Laboratory (DEMATEL) is effective at identifying cause-and-effect relationships in complex problems but does not yield structured hierarchies of influence [111].

TISM overcomes the aforementioned limitations and uniquely integrates interpretation, hierarchy, and causal logic [78,112,113]. It captures transitive relationships, enhances theoretical development by explicitly addressing the "why," and transforms complex systems into accessible, well-structured models [114]. Furthermore, TISM enables the creation of a coherent structural model that reveals the layered influence of various barriers, critical for understanding systemic resistance to smart mobility. The method's ability to incorporate stakeholder reasoning and build consensus around interdependencies enhances its practical relevance for smart mobility.

4. Data Analysis and Results

4.1. Data Collection and Analysis

The data collection and analysis process for this study followed a structured three-phase approach. In the initial phase, a list of 31 potential barriers to smart mobility adoption was compiled. This list was informed by a review of relevant literature, expert consultations. These barriers represent a broad range of institutional, technological and user-level challenges.

In the second phase, a panel of domain experts with over a decade of professional experience in transport planning and smart mobility was engaged to evaluate the relevance and significance of the identified barriers. Experts were selected through purposive sampling, a strategy well-suited for studies requiring rich, experience-based input. This sampling approach is appropriate due to its ability to ensure flexibility and convenience for participants, access to in-depth, context-sensitive insights grounded in practical experience, and support for asynchronous, reflective engagement [115,116].

In line with [117], a pre-screening process was undertaken to ensure that only well-informed participants were included. All selected respondents had professional experience ranging from seven to thirty years across diverse roles. The panel comprised, two academic experts in transport planning and smart urban systems, each with over 20 years of teaching and research experience. In addition, the panel drew from three practitioners from the transport sector (two from government agencies and one from a private mobility firm), each with more than twenty-five years of professional experience in transport policy, planning, or digital mobility services. This number of experts is deemed sufficient considering it smart mobility is a narrow and growing field and recent studies in nascent fields have used similar samples [118,119]. The list of experts is presented in Table 2.

Table 2. List of Experts.

Expert	Sector	Role / Title	Experience Area
E1	Academia	Professor of Urban Transport	Smart mobility policy, urban governance
E2	Government	Senior Urban Planner (City Transport Dept.)	Multi-modal transport planning
E3	Industry	Head of Operations, Ride-hailing Platform	Platform-based mobility service delivery
E4	Civil Society	Director, Mobility and Access NGO	Inclusive design and transport justice
E5	Regulator	Officer, National ICT Authority	Data governance, privacy, and digital infrastructure

Data collection was carried out at mutually convenient times. The interview gathered relevant demographic and professional information and presented the 14 selected barriers. Respondents were asked to perform pairwise comparisons to assess causal relationships between each pair of barriers, with the row representing the cause and the column the effect. For each pair, a value of "1" indicated the presence of a relationship, while "0" indicated no relationship. Where a relationship was identified, respondents were also asked to explain the rationale, adding interpretive depth to the data. The data collection tool is presented in Appendix A.

4.2. Analysis of the Barriers

To ensure methodological rigor in determining consensus among the experts, the Gage Repeatability and Reproducibility (Gage R&R) technique was employed. This method evaluates the level of agreement among raters in qualitative assessments. Following the benchmark established by [120], a consensus score exceeding 80% was considered indicative of acceptable reproducibility and inter-rater reliability. Based on this criterion, 14 out of the initial 31 barriers met the inclusion threshold and were retained for further analysis using the Total Interpretive Structural Modelling (TISM) methodology. The initial reachability matrix was developed based on the cumulative input of five experts. A consensus rule was applied: if three or more respondents rated a particular relationship as "1," the corresponding matrix entry was marked as "1"; otherwise, it was marked as

“0.” This approach ensured both rigor and reliability in capturing expert agreement and laid the foundation for the subsequent TISM analysis.

4.2. Procedure for Conducting Total Interpretive Structural Modelling (TISM)

The Total Interpretive Structural Modelling (TISM) procedure applied in this study followed a structured and iterative set of steps designed to identify, analyze, and interpret the interrelationships among the most critical barriers to smart mobility adoption.

Step 1: Identification of Key Barriers

The process began with an identification of barriers based on a mini literature review, expert consultations. A final list of 14 validated barriers was established for modeling (see Section 3.1).

Step 2: Establishing Contextual Relationships

To investigate how the identified barriers interact, a contextual relationship was defined for each pair as follows: “Barrier i influences or enhances Barrier j.” These directional relationships were elicited through a pairwise comparison process, where experts assessed the extent to which one barrier affects another. For each pair (Bi, Bj), experts were asked to indicate their level of agreement with the proposed influence using one of three responses: (1) Agree, (2) Neutral, or (3) Disagree.

Given that 14 barriers were selected for analysis, this yielded a total of 182 pairwise comparisons (14 × 13). To determine whether a relationship exists between two barriers, a consensus threshold was applied: if at least 50% of expert responses indicated agreement, the relationship was considered valid and retained; otherwise, it was discarded as non-significant [103,109,118]. This approach ensured that only those directional links with collective expert support were incorporated into the structural model, thereby enhancing the reliability of the relationship mapping and enabling the identification of causal linkages across the system.

Step 3: Construction of the Structural Self-Interaction Matrix (SSIM)

Expert input was used to assess the existence and direction of influence for every possible pair of the 14 barriers. The SSIM was developed based on four possible relationships and presented in Table 3

- V: Barrier i influences Barrier j
- A: Barrier j influences Barrier i
- X: Barriers i and j influence each other
- O: No relationship exists between Barriers i and j

The SSIM matrix, reflecting expert judgments, is presented in Table 3.

Table 3. SSIM Matrix.

Barriers	B14	B13	B12	B11	B10	B9	B8	B7	B6	B5	B4	B3	B2	B1
B1:Fragmented institutional mandates	O	V	V	V	O	V	A	V	V	V	O	O	V	X
B2:Lack of inter-operability and information on multimodal journeys and Integration	O	V	O	A	A	A	A	A	V	A	O	A	X	
B3:Inadequate digital infrastructure	O	V	O	V	O	O	A	A	V	A	O	X		
B4:Data privacy and security concerns	A	V	V	V	O	O	A	V	V	A	X			
B5:Existing regulations and policies are not favorable for Smart Mobility	O	V	V	V	V	V	A	A	V	X				
B6 Absence of inclusive design	O	V	O	V	A	A	O	A	X					
B7 Political resistance	O	V	O	V	O	V	A	X						
B8 Legacy paradigms in CTP	O	V	V	V	V	V	X							

B9:Lack of appeal of public transport	O	V	V	O	O	X
B10:Lack of safe environment for pedestrians and cyclists	O	V	V	V	X	
B11:Lack of coverage -smart mobility not extensively covered	O	V	V	X		
B12:Loss of car as status symbol and personal space (e.g flexibility).	O	A	X			
B13:Affordability of smart mobility services	O	X				
B14:Digital literacy gaps	X					

Source: Authors' own creation.

Step 4: Binary Interpretation of Relationships

Once the valid relationships were established, they were encoded into a binary matrix to construct the initial reachability matrix. This square “ $n \times n$ ” matrix (where n is the number of barriers) captures the direct influence of each barrier on another. Specifically, cell (i, j) represents the influence of Barrier i on Barrier j , and is coded as:

- 1, if a direct influence exists (as agreed upon in Step 2),
- 0, if no influence is identified.

This binary representation simplifies the analysis of interrelationships and provides a foundation for subsequent hierarchical structuring. By default, all diagonal elements in the matrix (i.e., where $i = j$) are assigned a value of 1, indicating that each barrier is assumed to influence itself, in line with conventional practice [78,101,109]. The initial reachability matrix is presented in Table 4.

Table 4. Initial Reachability Matrix.

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14
B1:Fragmented institutional mandates	1	1	0	0	1	1	1	0	1	0	1	1	1	0
B2: Lack of inter-operability and information on multimodal journeys and Integration	0	1	0	0	0	1	0	0	0	0	0	0	1	0
B3: Inadequate digital infrastructure	0	1	1	0	0	1	0	0	0	0	1	0	1	0
B4:Data privacy and security concerns	0	1	0	1	0	1	1	0	0	0	1	1	1	0
B5: Existing regulations and policies are not favorable for Smart Mobility	0	1	1	1	1	1	0	0	1	1	1	1	1	0
B6: Absence of inclusive design	0	0	0	0	0	1	0	0	0	0	1	0	1	0
B7: Political resistance	0	1	1	0	1	1	1	0	1	0	1	0	1	0
B8: Legacy paradigms in CTP	1	1	1	1	1	0	1	1	1	1	1	1	1	0
B9: Lack of appeal of public transport	0	1	0	0	0	1	0	0	1	0	0	1	1	0
B10: Lack of safe environment for pedestrians and cyclists	0	1	0	0	0	1	0	0	0	1	1	1	1	0
B11: Lack of coverage -smart mobility not extensively covered	0	1	0	0	0	0	0	0	0	0	1	1	1	0
B12: Loss of car as status symbol and personal space (e.g flexibility).	0	0	0	0	0	0	0	0	0	0	0	1	0	0

B13: Affordability of smart mobility services	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
B14: Digital literacy gaps	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1

Source: Authors' own creation.

Step 5: Development of the Interpretive Logic Knowledge Base

An interpretive knowledge base was created, documenting the logical explanations for each confirmed relationship. Each barrier was compared with all others in a pairwise manner. If a relationship was affirmed ("Yes"), a justification was documented based on expert judgment and literature support.

Step 6: Reachability Matrix and Transitivity Check

To ensure logical consistency and completeness of the model, the principle of transitivity was applied. This rule posits that if Barrier A influences Barrier B, and Barrier B influences Barrier C, then Barrier A is assumed to indirectly influence Barrier C. All such inferred transitive relationships were systematically checked and incorporated into the matrix.

The resulting matrix thus reflects both the direct and transitive influences among the barriers, enabling the construction of a hierarchical structure in subsequent steps. The finalized reachability matrix, inclusive of transitive links, is presented in Table 5.

Table 5. Final Reachability Matrix with Transitivities.

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	Driving Power
B1:Fragmented institutional mandates	1	1	0	1	1	1	1	0	1	1	1	1	1	0	11
B2:Lack of inter-operability and information on multimodal journeys and Integration	0	1	0	0	0	1	0	0	0	0	1	1	1	0	5
B3:Inadequate digital infrastructure	0	1	1	0	0	1	0	0	0	0	1	1	1	0	6
B4:Data privacy and security concerns	0	1	1	1	1	1	1	0	1	1	1	1	1	0	11
B5:Existing regulations and policies are not favorable for Smart Mobility	0	1	1	1	1	1	1	0	1	1	1	1	1	0	11
B6: Absence of inclusive design	0	1	0	0	0	1	0	0	0	0	1	1	1	0	5
B7: Political resistance	0	1	1	1	1	1	1	0	1	1	1	1	1	0	11
B8: Legacy paradigms in CTP	1	1	1	1	1	1	1	1	1	1	1	1	1	0	13
B9:Lack of appeal of public transport	0	1	0	0	0	1	0	0	1	0	0	1	1	0	5
B10:Lack of safe environment for pedestrians and cyclists	0	1	0	0	0	1	0	0	0	1	1	1	1	0	6
B11:Lack of coverage - smart mobility not extensively covered	0	1	0	0	0	1	0	0	0	0	1	1	1	0	5

B12:Loss of car as status symbol and personal space (e.g flexibility).	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
B13:Affordability of smart mobility services	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2
B14:Digital literacy gaps Dependency Power	0	1	0	1	0	1	1	0	0	0	1	1	1	1	8
	2	12	5	6	5	12	6	1	6	6	11	14	13	1	

Step 7: Level Partitioning

Using the reachability matrix, level partitions were identified by determining the reachability and intersection sets for each barrier. Barriers with matching sets were placed at the same level in the hierarchy. This step was repeated iteratively until all barriers were assigned a hierarchical level. The level partitioning process is illustrated in Table 6.

Table 6. Partition Level Matrix of the Final Reachability Matrix.

Barrier	Iteration #1			Level
	Reachability Set	Antecedent Set	Intersection Set	
B1	B1,B2,B4,B5,B6,B7,B9,B10,B11,B12,B13	B1,B8	B1	
B2	B2,B6,B11,B12,B13	B1,B2,B3,B4,B5,B6,B8,B9,B10,B11,B14	B2,B6,B11	
B3	B2,B3,B6,B11,B12,B13	B3,B4,B5,B7,B8	B3	
B4	B2,B3,B4,B5,B6,B7,B9,B10,B11,B12,B13	B1,B4,B5,B7,B8,B14	B4,B5,B7	
B5	B2,B3,B4,B5,B6,B7,B9,B10,B11,B12,B13	B1,B4,B5,B7,B8	B4,B5,B7	
B6	B2,B6,B11,B12,B13	B1,B2,B3,B4,B5,B6,B7,B8,B9,B10,B11,B14	B2,B6,B11	
B7	B2,B3,B4,B5,B6,B7,B9,B10,B11,B12,B13	B1,B4,B5,B7,B8,B14	B4,B5,B7	
B8	B1,B2,B3,B4,B5,B6,B7,B8,B9,B10,B11,B12,B13	B8	B8	
B9	B2,B6,B9,B12,B13	B1,B4,B5,B7,B8,B9	B9	
B10	B2,B6,B10,B11,B12,B13	B1,B4,B5,B7,B8,B10	B10	
B11	B2,B6,B11,B12,B13	B1,B2,B3,B4,B5,B6,B7,B8,B10,B11,B14	B2,B6, B11	
B12	B12	B1,B2,B3,B4,B5,B6,B7,B8,B9,B10,B11,B12,B13,B14	B12	I
B13	B12,B13	B1,B2,B3,B4,B5,B6,B7,B8,B9,B10,B11,B13,B14	B13	
B14	B2,B4,B6,B7,B11,B12,B13,B14	B14	B14	
Iteration #2				
Barrier	Reachability Set	Antecedent Set	Intersection Set	
B1	B1,B2,B4,B5,B6,B7,B9,B10,B11,B13	B1,B8	B1	
B2	B2,B6,B11,B13	B1,B2,B3,B4,B5,B6,B8,B9,B10,B11,B14	B2,B6,B11	
B3	B2,B3,B6,B11,B13	B3,B4,B5,B7,B8	B3	
B4	B2,B3,B4,B5,B6,B7,B9,B10,B11,B13	B1,B4,B5,B7,B8,B14	B4,B5,B7	
B5	B2,B3,B4,B5,B6,B7,B9,B10,B11,B13	B1,B4,B5,B7,B8	B4,B5,B7	
B6	B2,B6,B11,B13	B1,B2,B3,B4,B5,B6,B7,B8,B9,B10,B11,B14	B2,B6,B11	
B7	B2,B3,B4,B5,B6,B7,B9,B10,B11,B13	B1,B4,B5,B7,B8,B14	B4,B5,B7	
B8	B1,B2,B3,B4,B5,B6,B7,B8,B9,B10,B11,B13	B8	B8	
B9	B2,B6,B9,B13	B1,B4,B5,B7,B8,B9	B9	
B10	B2,B6,B10,B11,B13	B1,B4,B5,B7,B8,B10	B10	
B11	B2,B6,B11,B13	B1,B2,B3,B4,B5,B6,B7,B8,B10,B11,B14	B2,B6, B11	
B13	B13	B1,B2,B3,B4,B5,B6,B7,B8,B9,B10,B11,B13,B14	B13	II
B14	B2,B4,B6,B7,B11,B13,B14	B14	B14	
Iteration #3				
Barrier	Reachability Set	Antecedent Set	Intersection Set	
B1	B1,B2,B4,B5,B6,B7,B9,B10,B11	B1,B8	B1	

B2	B2,B6,B11	B1,B2,B3,B4,B5,B6,B8,B9,B10,B11,B14	B2,B6,B11	III
B3	B2,B3,B6,B11	B3,B4,B5,B7,B8	B3	
B4	B2,B3,B4,B5,B6,B7,B9,B10,B11	B1,B4,B5,B7,B8,B14	B4,B5,B7	
B5	B2,B3,B4,B5,B6,B7,B9,B10,B11	B1,B4,B5,B7,B8	B4,B5,B7	
B6	B2,B6,B11	B1,B2,B3,B4,B5,B6,B7,B8,B9,B10,B11,B14	B2,B6,B11	III
B7	B2,B3,B4,B5,B6,B7,B9,B10,B11	B1,B4,B5,B7,B8,B14	B4,B5,B7	
B8	B1,B2,B3,B4,B5,B6,B7,B8,B9,B10,B11	B8	B8	
B9	B2,B6,B9	B1,B4,B5,B7,B8,B9	B9	III
B10	B2,B6,B10,B11	B1,B4,B5,B7,B8,B10	B10	
B11	B2,B6,B11	B1,B2,B3,B4,B5,B6,B7,B8,B10,B11,B14	B2,B6, B11	III
B14	B2,B4,B6,B7,B11,B14	B14	B14	
Iteration #4				
Barrier	Reachability Set	Antecedent Set	Intersection Set	
B1	B1,B4,B5,B7,B10	B1,B8	B1	
B3	B3	B3,B4,B5,B7,B8	B3	IV
B4	B3,B4,B5,B7,B10	B1,B4,B5,B7,B8,B14	B4,B5,B7	
B5	B3,B4,B5,B7,B10	B1,B4,B5,B7,B8	B4,B5,B7	
B7	B3,B4,B5,B7,B10	B1,B4,B5,B7,B8,B14	B4,B5,B7	
B8	B1,B3,B4,B5,B7,B8,B10	B8	B8	
B10	B10	B1,B4,B5,B7,B8,B10	B10	IV
B14	B4,B7,B14	B14	B14	
Iteration #5				
Barrier	Reachability Set	Antecedent Set	Intersection Set	
B1	B1,B4,B5,B7	B1,B8	B1	
B4	B4,B5,B7	B1,B4,B5,B7,B8,B14	B4,B5,B7	V
B5	B4,B5,B7	B1,B4,B5,B7,B8	B4,B5,B7	V
B7	B4,B5,B7	B1,B4,B5,B7,B8,B14	B4,B5,B7	V
B8	B1,B4,B5,B7,B8	B8	B8	
B14	B4,B7,B14	B14	B14	
Iteration #6				
Barrier	Reachability Set	Antecedent Set	Intersection Set	
B1	B1	B1,B8	B1	VI
B8	B1,B8	B8	B8	
B14	B14	B14	B14	VI
Iteration #7				
Barrier	Reachability Set	Antecedent Set	Intersection Set	
B8	B8	B8	B8	VII

Step 8: Development of the Digraph

A directed graph (digraph) was constructed to visualize the hierarchical structure and relationships among the barriers. Arrows were used to denote directional influences between elements based on the reachability matrix. This graphical representation is shown in Figure 1.

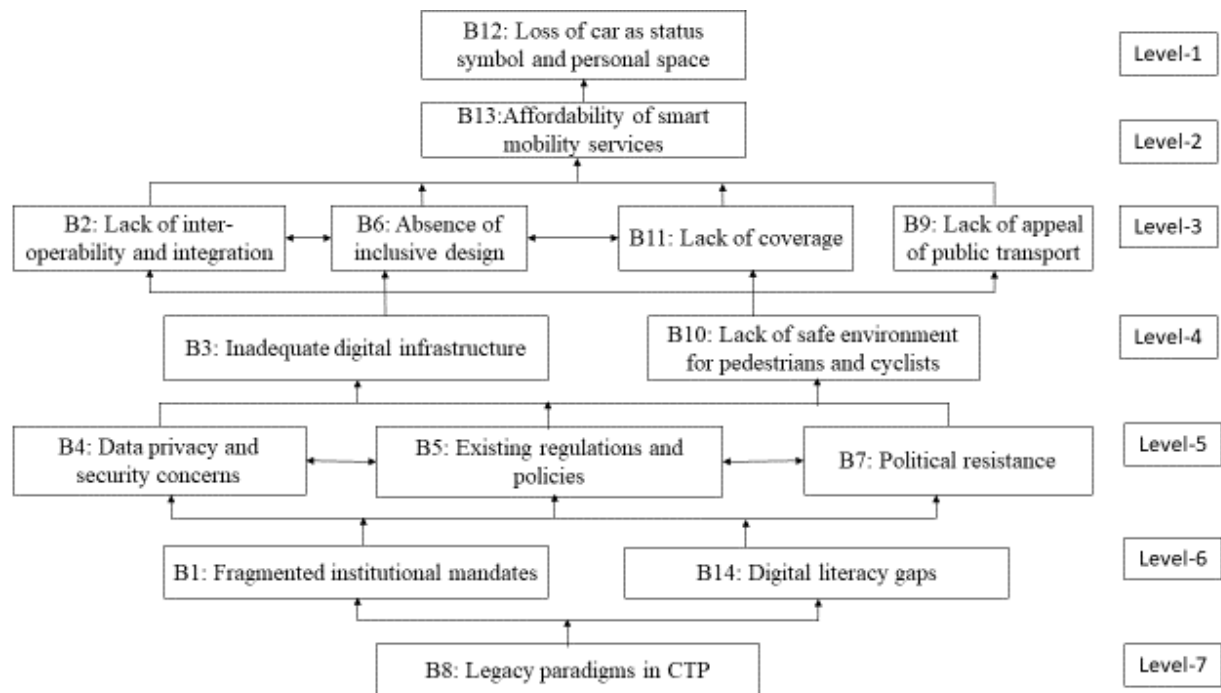


Figure 1. TISM hierarchical Model for Smart Mobility Barriers.

The level partitioning process arranged the 14 barriers to smart mobility adoption into a seven-level hierarchy based on their driving and dependence relationships (see Table 6). At the base of the hierarchy, B8: Legacy paradigms in conventional transport planning (CTP) was positioned at Level VII, indicating it as the most foundational barrier influencing others but not directly influenced itself. Similarly, B1: Fragmented institutional mandates and B14: Digital literacy gaps occupy Level VI, highlighting their systemic influence across regulatory and user domains.

Mid-level barriers such as B5: Unfavorable regulations, B4: Data privacy concerns, and B7: Political resistance (Level V) act as both influencers and recipients of influence. These barriers typically represent policy-related and governance constraints that both shape and respond to institutional and technological challenges.

The other barriers such as B3: Inadequate digital infrastructure and B10: Lack of safe pedestrian and cyclist environments fall under Level IV, indicating their intermediate structural importance. These are technical and infrastructural issues that are influenced by high-level governance barriers but also shape user-level perceptions.

User-experience-focused barriers like B2: Lack of inter-operability, B6: Absence of inclusive design, B9: Lack of appeal of public transport, and B11: Limited coverage of smart mobility appear in Level III, demonstrating their dependence on upstream technical and regulatory conditions.

At the top of the model, B13: Affordability of smart mobility services (Level II) and B12: Loss of car as a status symbol and personal space (Level I) are positioned as the most dependent barriers. These represent end-user concerns that are largely shaped by upstream system, policy, and infrastructure factors.

Step 9: Construction of the Final TISM Model

The final TISM model (Figure 1) was developed by translating the digraph into an interpretive structural framework. This model illustrates both direct and transitive relationships among the barriers and reflects the cumulative insights gathered through literature, expert interpretation, and TISM logic. Further, based on the explanation of the experts, an interpretive logic was added to each relationship as presented in Table 7.

Table 7. The Interpretive Matrix.

From Barrier	To Barrier	Interpretation of Influence	Supporting Literature
B8: Legacy paradigms in CTP	B1: Fragmented institutional mandates	Outdated planning practices in conventional transport (e.g., car-centric, siloed approaches) continue to shape institutional mandates, leading to fragmented roles among agencies. This weakens coordination and undermines integrated mobility planning.	[16,20]
B8	B14: Digital literacy gaps	Legacy systems often marginalize digital innovation and public ICT education, contributing to inadequate digital literacy among users and decision-makers.	[19]
B1: Fragmented institutional mandates	B4: Data privacy and security concerns	Fragmented institutional structures lack unified standards or oversight mechanisms for managing mobility data securely, increasing user concerns over privacy and data misuse.	[121]
B1	B5: Unfavorable regulations and policies	Disjointed mandates lead to inconsistent or outdated policy frameworks that do not support smart mobility innovations such as e-hailing, shared micromobility, or MaaS platforms.	[122,123]
B1	B7: Political resistance	Institutional fragmentation dilutes accountability and policy leadership, making it easier for entrenched political interests to resist disruptive mobility reforms.	[124]
B14: Digital literacy gaps	B4: Data privacy and security concerns	Users with limited digital literacy are more likely to be wary of data privacy issues, leading to reluctance in using app-based smart mobility services.	[125]
B14	B5: Unfavorable regulations and policies	Poor digital understanding among decision-makers hampers the development of responsive policies that address smart mobility governance and regulation.	[126]
B14	B7: Political resistance	Political leaders with low digital fluency may perceive smart mobility initiatives as risky or unmanageable, leading to resistance or policy inertia.	[16]
B4, B5, B7	B3: Inadequate digital infrastructure	Data privacy concerns (B4), outdated policies (B5), and political reluctance (B7) delay investment in and deployment of essential digital infrastructure for smart mobility (e.g., sensors, real-time data platforms).	[20]
B4, B5, B7	B10: Lack of safe environments for cyclists and pedestrians	Data privacy concerns (B4), outdated policies (B5), and political reluctance (B7) prevent urban redesign that accommodates active mobility and smart infrastructure like connected crossings or bike-tracking apps.	[84]
B3, B10	B2: Lack of interoperability and integration	Poor digital infrastructure (B3) limits the ability to interconnect transport modes, while unsafe streets (B10) reduce the feasibility of integrating active travel into mobility-as-a-service (MaaS) platforms.	[70]
B3, B10	B6: Absence of inclusive design	Limited infrastructure investment and inadequate safety planning lead to systems that do not account for the needs of vulnerable users (e.g., elderly,	[127]

		disabled and marginalised), undermining inclusivity.	
B3, B10	B11: Limited coverage	Poor infrastructure and unsafe environments constrain the geographic and demographic reach of smart mobility services, particularly in peripheral or underserved areas.	[128]
B3, B10	B9: Lack of appeal of public transport	Poor infrastructure and safety concerns discourage the use of public transport and make it less attractive in comparison to private vehicles.	[126]
B2, B6, B9, B11	B13: Affordability of smart mobility services	Fragmentation, exclusivity, poor coverage, and unappealing alternatives reduce economies of scale, increase operational costs, and pass affordability burdens to users.	[129]
B13	B12: Loss of car as a status symbol and personal space	When smart mobility becomes affordable, accessible, and comprehensive, it begins to offer a viable alternative to private car ownership, challenging cultural norms and attachment to personal vehicles.	[74,130]

4.3. MICMAC Analysis

To complement the structural insights generated by the TISM model, a MICMAC analysis (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement) was performed to assess the driving and dependence power of each identified barrier [112]. MICMAC enables a systematic classification of elements based on their systemic influence and susceptibility, offering a strategic framework for prioritizing policy and planning interventions [131,132]. The outcome is illustrated in Figure 2.

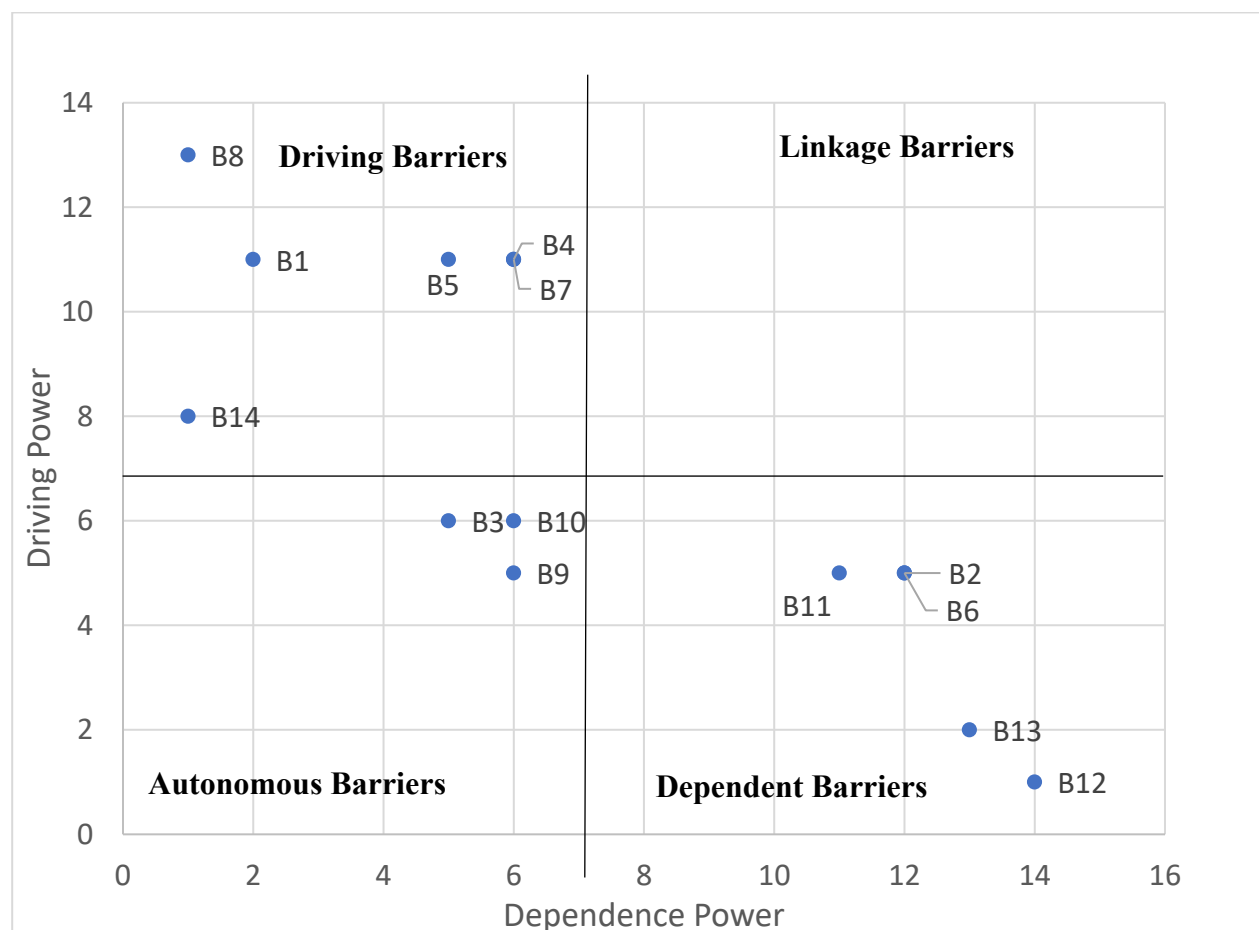


Figure 2. MICMAC Analysis. infrastructure; B4=Data privacy and security; B5=Existing regulations and policies; B6=Absence of inclusive design; B7=Political resistance; B8=Legacy Paradigms in CTP; B9=Lack of public transport appeal; B10=Lack of safe environment for pedestrians and cyclists; B11=Lack of coverage; B12=Loss of car as status symbol and personal space; B13=Affordability; B14=Digital literacy gaps. **Source:** Authors' own creation.

The barriers were grouped into four quadrants as presented in the subsequent section:

4.3.1. Driving Barriers

These are barriers with high driving power but low dependence. These are foundational barriers that exert influence over many others and thus serve as strategic leverage points for intervention. In this study, six driving barriers fall in this category, namely: legacy paradigms in CTP (B8), fragmented institutional mandates (B1), unfavorable regulations and policies (B5), data privacy and security (B4), political resistance (B7) and digital literacy gaps (B14).

B8 (Legacy paradigms in CTP), consistent with [16] and [20], emerges as the most influential root barrier reinforces outdated infrastructure priorities, entrenches car-centric development, and obstructs the shift toward data-driven, user-centric smart mobility models. This foundational constraint exacerbates B1 (Fragmented institutional mandates), a condition noted by [19] and [133], which leads to incoherent governance and impedes integrated transport solutions.

4.3.2. Dependent Barriers

These barriers have low driving power but high dependence. They are typically the outcomes of deeper systemic issues and include: limited coverage of smart mobility (B11), lack of interoperability and multimodal integration (B2), absence of inclusive design (B6), affordability constraints (B13) and loss of car as status symbols or personal space B12). B12, which sits at the top of the model, highlights how personal attitudes and social values surrounding car ownership persist as the final obstacles in the shift toward sustainable urban transport. Similar observations are reported by [74] and [129] who argue that car use is often culturally reinforced and emotionally driven. However, the dependent barriers can only be meaningfully addressed once systemic issues at the institutional and technological levels are resolved.

4.3.3. Linkage Barriers

These elements exhibit both high driving and high dependence power, making them unstable and dynamic within the system [102,134]. They typically influence and are influenced by multiple other barriers. Interestingly, no elements were identified in this category, suggesting a relatively structured separation between foundational and symptomatic barriers in this study.

4.3.4. Autonomous Barriers

These barriers have both low driving and low dependence power, indicating their relative disconnection from the system's core dynamics. The following barriers fall under this category: inadequate digital infrastructure (B3), lack of appeal of public transport (B9) and lack of safe environment for cyclists and pedestrians (B10). While these factors may not significantly shape or be shaped by the systemic structure, they remain important for direct user experience and public acceptance. For example, lack of safe infrastructure continues to be a deterrent for non-motorized mobility in many cities [70,84].

The MICMAC analysis enriches the findings from TISM by identifying high-leverage intervention points. Barriers such as legacy planning paradigms (B8), institutional fragmentation (B1), and regulatory resistance (B5) stand out as the most influential and should be addressed first to trigger cascading improvements across the system [124]. Meanwhile, dependent and autonomous

barriers, although less influential, should be integrated into long-term strategies that build public trust, increase access, and encourage behavioral shifts toward smart mobility.

5. Discussion, Implications and Limitations

5.1. Discussion

The study set out to examine the barriers to smart mobility adoption and to map their structural interrelationships using Total Interpretive Structural Modelling (TISM) and MICMAC analysis. The results reveal that barriers to smart mobility are not isolated or purely technical, but are embedded within a system of institutional, political, and socio-cultural constraints. Through the lens of the Critical Urban Theory (CUT), the study revealed that smart mobility adoption is shaped by entrenched power structures, car-centric urban paradigms, and governance arrangements that reproduce inequality in urban mobility systems.

At the base of the TISM hierarchy, legacy paradigms in conventional transport planning (CTP) emerged as the most influential barrier. These paradigms, anchored in car-centric development, traffic-flow optimization, and path-dependent infrastructure choices, systematically undermine the transition to smart mobility [54,56,135]. From the critical urban theory perspective, this trend reflects how transportation planning institutions have historically been aligned with growth-oriented, automobile-dependent models of urbanization [62,136]. Rather than neutral policy tools, legacy planning frameworks represent a form of urban political economy that privileges private car ownership while marginalizing collective and active modes of transport.

Furthermore, the entrenched legacy systems tend to directly influence institutional fragmentation (B1), which further hampers coordination among agencies, perpetuating governance silos, weak coordination, and inconsistent objectives across transport, ICT, and urban development agencies [16,70]. These fragmented mandates illustrate how overlapping institutional logics protect vested interests and resist disruptive reforms, thereby obstructing transformative mobility transitions. As noted by [137], the paradigm is yet to shift and may take radical approaches to upend the existing system.

The middle layers of the model depict the role of unsupportive regulations, political resistance, and weak data governance as systemic barriers. Political resistance, in particular, reflects entrenched coalitions, namely car lobbies, fuel industries, and political actors that defend the status quo for ideological and economic gain [31]. Regulatory gaps exacerbate this resistance by creating uncertainty and deterring private investment in innovative services [51]. These barriers exemplify the “politics of urban mobility,” where institutional arrangements are not passive but actively reproduce inequality and exclusion [18]. They also highlight how governance failures cascade downstream, influencing user-facing concerns such as affordability, service quality, and trust in digital systems. For instance, the lack of inclusive design and multimodal integration tend to reinforce perceptions that smart mobility is inaccessible or inconvenient, especially for marginalized users [138–140].

At the dependent end of the hierarchy, barriers such as affordability, digital literacy gaps, safety for non-motorized users, and car ownership as a cultural status symbol emerge as outcomes rather than root causes. These findings align with socio-technical transition theory, which posits that user-level change is unlikely without supportive structural conditions [141,142]. This insight is important as it shows that exclusionary practices in technology adoption such as reliance on app-based platforms in contexts with weak digital infrastructure may reproduce existing urban inequalities [63,143]. For example, car ownership as a status symbol persists not simply because of individual preferences, but because unreliable public transport and fragmented governance reinforce its cultural and economic value [74,80]. Similarly, affordability concerns are symptomatic of institutional inefficiencies and fragmented digital ecosystems that constrain economies of scale. These findings suggest that smart mobility adoption cannot be achieved through behavioral campaigns alone but requires systemic restructuring [144,145].

The MICMAC analysis complemented the TISM findings by classifying the barriers into driving, dependent, and autonomous categories. The identification of legacy paradigms, institutional fragmentation, and regulatory weaknesses as high-driving-power barriers confirms their role as leverage points for system-wide change. These insights are consistent with previous research emphasizing the importance of tackling root causes rather than surface-level symptoms [98]. The findings are also consistent with previous studies that have posited that transport planning is the leverage point and holds the key to addressing the root causes of car-centric paradigms [56].

5.2. Implications for Theory and Policy

This study offers a theoretical contribution to mobility transition research through a combination of TISM with MICMAC analysis. It demonstrates that barriers are not only hierarchically structured but also interdependent, with high-driving-power barriers (e.g., legacy paradigms, fragmented mandates, political resistance) functioning as leverage points for systemic change. In contrast, autonomous barriers such as digital infrastructure or public transport appeal appear disconnected from the structural core, cautioning against piecemeal interventions.

Theoretically, the integration of critical urban theory into this analysis extends existing socio-technical perspectives by foregrounding power, inequality, and institutional resistance as central dynamics in smart mobility adoption. It reframes the transition not as a neutral technological shift but as a contested socio-political process embedded in broader urban contradictions. For policymakers, the results emphasize the need to prioritize structural reforms such as governance integration, regulatory clarity, and institutional paradigm shifts as opposed to narrow technical fixes.

5.3. Study Limitations and Future Research Directions

While the study provides new insights, several limitations exist and should be acknowledged. First, the reliance on expert judgments to develop the Structural Self-Interaction Matrix (SSIM) may introduce subjectivity, as expert perspectives can be shaped by their institutional affiliations and professional biases. Second, the focus on a single urban context limits generalizability; mobility challenges may manifest differently across cities with varying governance models, levels of digital maturity, and socio-economic conditions. Third, while TISM and MICMAC capture structural relationships, they provide a static view of barriers and do not account for dynamic changes over time. Future research could address these limitations by incorporating longitudinal data, comparative cross-city analyses, and mixed-method approaches such as fuzzy-set Qualitative Comparative Analysis (fsQCA) or Agent-Based Modeling (ABM).

6. Conclusions

This study examined the barriers to smart mobility adoption by integrating Total Interpretive Structural Modelling (TISM) and MICMAC analysis to uncover their hierarchical structure, interdependencies, and systemic influence. The analysis revealed that legacy paradigms in conventional transport planning, fragmented institutional mandates, and regulatory weaknesses are not just technical hurdles but foundational structural barriers that shape downstream constraints such as affordability, limited coverage, and user resistance. In contrast, issues such as inadequate digital infrastructure or the appeal of public transport emerged as relatively autonomous, highlighting the limited impact of addressing them in isolation.

Theoretically, this study advances the literature by moving beyond isolated or user-centric perspectives to offer a structural and critical understanding of smart mobility barriers. By drawing on Critical Urban Theory, the study demonstrates that resistance to smart mobility adoption is deeply embedded in the institutional, political, and socio-cultural fabric of urban governance. Rather than framing adoption challenges as mere technical deficits or individual choices, the findings underscore the role of entrenched power relations, car-centric legacies, and systemic inequities in shaping mobility futures.

Practically, the results highlight clear leverage points for policymakers and planners. Targeting high-driving-power barriers such as institutional reform, regulatory alignment, and paradigm shifts in transport planning may offer the potential for cascading system-wide effects. Without such structural interventions, efforts to promote smart mobility through pricing adjustments, digital upgrades, or behavioral campaigns risk being incremental and insufficient.

Finally, while the study offers new theoretical and practical insights, it also points to avenues for future research. Comparative and longitudinal studies are needed to examine how these barriers evolve across different urban contexts, particularly in the Global South, where institutional and infrastructural deficits are more pronounced. Methodological extensions combining TISM with fsQCA or Agent-Based Modeling could further illuminate how interventions at leverage points interact under dynamic and uncertain conditions.

Appendix A

Appendix A. Data Collection tool

Section	Item/Question	Responses Format
A. Background Information	1. Please indicate your current role/affiliation (e.g., policymaker, academic, practitioner, private sector).	Open-ended
	2. How many years of experience do you have in the field of urban mobility, transport planning, or related areas?	Number of Years
B. Barrier Validation	3. Please rate the relevance of each barrier (list of 31 barriers provided in a separate sheet) to smart mobility adoption in your context.	5-point Likert scale (1=Not Relevant, 5=Highly Relevant)
	4. From your experience, are there barriers not captured in this list? Please specify.	Open-ended
C. Barrier Interrelationships (TISM Input)	5. Do you believe Barrier X influences Barrier Y? (Pairwise comparisons of 14 barriers presented in matrix form).	Response options: V (X influences Y), A (Y influences X), X (Mutual influence), O (No relation).
	6. Please provide a brief explanation for your judgment (why/how one barrier influences another).	Open-ended

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