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Built Environment Performance and User Perception of Urban Transit Interface: A Mixed-Methods Empirical Assessment of Bus Corridor in Udupi, India

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Abstract

Transit accessibility is a critical determinant of urban equity (SDG-11) in the Global South, a term referring to emerging economies characterised by rapid urbanisation and significant infrastructure deficits. A significant 'compliance–resilience gap' persists in intermediate Indian cities. This study evaluates a 10.2 km primary transit corridor in Udupi, auditing 42 transit interfaces across 21 nodes using a unified 14-parameter framework. Analytical reliability was confirmed via inter-rater reliability testing (Krippendorff's alpha = 0.822). Using a joint display synthesis, technical compliance failures were mapped to qualitative user narratives. Results supported Hypothesis 1 (H1) via chi-square testing, revealing systemic failures ($p < 0.05$) in ramps (2%) and information systems (0%). Hypothesis 2 (H2) was validated through a one-sample *t*-test, showing that stakeholder perception (mean = 1.55) was statistically significantly lower than the neutral threshold ($t(99) = -21.10$, $p < 0.001$). These deficits triggered restrictive user adaptation strategies, including temporal displacement and forced social dependency. The study establishes a replicable 'justice-centred' audit framework to prioritise interventions in resource-constrained urban contexts.

Keywords: urban mobility; transit node performance; urban transit interface; transport equity; inter-rater reliability (IRR); citizen perception; sustainable urban mobility; accessibility; locomotor disabilities; India

1. Introduction

The creation of inclusive, safe, resilient, and sustainable cities is the primary goal of the United Nations Sustainable Development Goals (SDG 11) [1]. Within this broader vision, accessible public transportation plays a crucial role in ensuring equity and participation, particularly for persons with disabilities (hereinafter referred to as PwD) [2]. The United Nations Convention on the Rights of Persons with Disabilities (UNCRPD) [3] recognises accessibility as a fundamental right that enables independent living and meaningful social engagement of PwD. The architectural and technical detailing of transit nodes determines the threshold between independent mobility and systematic social exclusion.

However, a noticeable gap exists between policy commitments and the level of implementation. This gap is more visible in the context of rapidly urbanising developing nations like India [4]. The significance of the study is based on the stark divide between the metropolitan and intermediate urban ecosystems. The need for this study is grounded in the distinct quantitative divide between metropolitan cities and intermediate cities. In

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the Indian state of Karnataka, its capital Bengaluru, a metropolitan city, exhibits >70% adherence to accessibility standards in transit hubs and has integrated low-floor buses. Intermediate cities like Udupi rely on a 90% share of private sector bus operators with a fleet of only high-floor buses. Recent empirical audits in Udupi indicate accessibility adherence levels as low as 14–35% for public buildings [5,6], significantly below what is found in metro cities. No audits have been carried out for the transit nodes of Udupi, and so data do not exist. This divergence is driven by administrative decisions and capital investment imbalances. The bus fleet in Udupi consists primarily of high-floor private vehicles with a step height of more than 900 mm, far exceeding the 400 mm standard found in wheelchair-accessible low-floor buses of Bangalore [7]. Furthermore, financial data from the Comptroller and Auditor General of India (CAG) Performance Audit [8] indicate a funding vacuum for intermediate cities. At the same time, metropolitan hubs benefit from dedicated grants like the Smart Cities Mission [9]. Intermediate cities like Udupi, which have been excluded from such funding schemes, are forced to rely on local municipal funds that are frequently inadequate. A detailed comparison between a metro city—Bangalore—and an intermediate city—Udupi—is presented in Table 1.

Table 1. Comparison between metro city and intermediate city.

Sl. No.	Aspect Compared	Metropolitan Cities (e.g., Bangalore)	Intermediate City (e.g., Udupi)
1	Accessibility adherence [5,6,9]	>70% in metro/bus hubs	14–35% (public buildings)
2	Bus floor height [7,10]	400 mm–650 mm (low-floor government buses)	above 900 mm (mostly high-floor private buses)
3	Use of public transport by persons with disabilities (PwDs)	60% of PwDs use public transit [11]	Estimated <10% Exact data not available
4	Availability of footpaths [12]	47% Availability	Discontinuous/lacking
5	Investments in infrastructure projects [8,9,13]	Multi-million-dollar investments since being the state capital, metro city, and part of the Smart City Mission.	Reliance on only municipal funds
6	Smart city funding by central and state governments [9,13]	110 million USD spent till June 2024	Nil Udupi is not part of the Smart City Mission

This study evaluates accessibility in bus transit hubs of Udupi, a representative intermediate city in the state of Karnataka, India. These urban centres, which are often classified as 'Tier-III'—an administrative category in India for cities with populations between 100,000 and 1,000,000 in the Indian administrative and economic context [14], are globally recognised as 'intermediate cities' [15]. Intermediate cities act as critical nodes for regional and social connectivity but often lag behind metropolitan regions in inclusive transport implementation. While major metropolitan regions receive attention, investments, and initiatives for enhancing accessible infrastructure, intermediate cities are often neglected [16]. Accessibility research in intermediate cities is critical since they face the unique challenge of haphazard incremental growth of infrastructure without centralised planning of a typical larger transit system and they lag in addressing accessibility needs [17,18]. A socially sustainable urban mobility approach requires that accessibility assessments look beyond infrastructure to broader project contributions for marginalised groups [19]. While global urban planning discourses, especially in European contexts like Brussels, are increasingly exploring high-tech sustainability through shared autonomous vehicles and car-free city

initiatives [20,21], intermediate cities in the Global South face fundamental accessibility deficits. In these contexts, mitigation of fundamental physical barriers to enable rudimentary accessible mobility is prioritised. Intermediate cities in the Global South often operate on older, outdated, and inadequately planned transportation systems. Most Indian intermediate cities depend heavily on bus-based transport, as alternative systems such as suburban rail and metros are absent. In such contexts, bus transport becomes the primary and often the only affordable public mobility option. It represents the primary site of interaction between the transit built environment and the citizens. It is likely to continue to do so until a better and more affordable mode of public transport is developed. Lack of adequate public transport has resulted in exponential growth in private vehicles, resulting in congestion and pollution across cities. For individuals who cannot afford to own private vehicles or pay for cab-based services, public transport is the primary mode of transport. The development of sustainable and affordable public transportation, such as bus transportation systems, is the need of the hour [22]. Persons with locomotor disabilities, hereinafter referred to as PwLD, not only encounter physical barriers like a lack of ramps, kerbs, and uneven surfaces but also have to face operational and informational challenges. It restricts their independent movement and makes routine travel stressful, unsafe, and dependent. This impacts their participation in education, employment, recreation, healthcare, and social life. The architectural and operational detailing of these transit nodes determines the threshold between social mobility and systematic exclusion [23].

The present study focuses on the accessibility of urban transit interfaces in Udupi, a growing regional hub, with an average of 45,000 daily bus ridership for a city with a total population of less than 200,000. Despite a large floating population and high dependence on bus transport, the bus infrastructure has evolved in an incremental manner. It presents an ideal case study for assessing the "compliance gap" between national accessibility guidelines and ground-level infrastructure. Based on 14 identified accessibility parameters [24], this study undertakes a systematic, field-based assessment of 42 transit interfaces at 21 transit nodes in Udupi. The study integrates physical measurements of existing infrastructure along with user perspectives. This is to not only understand whether accessibility features exist but also to know whether they function effectively for PwLD, one of the most prevalent disabilities in India [25]. This study, by integrating analysis of on-site observations and lived experiences of users, seeks to contribute through context-specific empirical evidence to the urban planning aspects of inclusive design of bus transport infrastructure. It tries to move beyond theoretical compliance and examines how accessibility is experienced in everyday transit environments of an intermediate Indian city [26,27].

To summarise, this study advances the domain of inclusive mobility through a threefold contribution.

- Methodological advancement: It operationalises a 'joint display synthesis' that explicitly maps technical compliance failures to physiological user strain;
- Empirical contribution: It quantifies the 'compliance–resilience gap' in an intermediate city characterised by fragmented private sector governance and a funding vacuum;
- Replicable framework: It establishes a 'justice-centred' audit protocol that practitioners in data-poor environments can use to prioritise high-impact interventions.

The Hypotheses

To provide a clear benchmark for evaluation, this study tests the following two hypotheses.

H1. *There is a statistically significant compliance gap between accessibility guidelines and the functional performance across the transit corridor (evaluated via chi-square goodness-of-fit test).*

H2. *Built environmental barriers act as triggers for restrictive usage and behavioural adaptations among PwLD (validated via one-sample t-test).*

2. Literature Review

2.1. Theoretical Framework: Universal Design and Accessibility

Universal design (UD) [28] provides the foundation for this study, translating into requirements for adequate circulation and accessible boarding points [27,29–31]. However, in resource-constrained cities, accessibility is often secondary to cost and retrofitting challenges [32]. This results in accessibility concerns being addressed in fragments rather than as part of a comprehensive planning approach.

2.2. Accessibility Parameters in Bus Transportation

Earlier studies and national/international guidelines have identified several key factors for evaluating accessibility in bus transportation systems [24,33]. These factors can be grouped into the following three broad domains.

- Physical infrastructure: This includes ramp design and its gradients, kerb cuts, surface finishes, lighting, seating design, waiting, circulation spaces, and railings [34,35];
- Service-related factors: This includes management and maintenance practices, safety measures, sanitation facilities, and availability of trained personnel [6,36];
- Information systems: This covers signage, real-time display systems, and accessible communication mechanisms [37].

Research has consistently shown that isolated improvements or retrofitting measures, such as installing a ramp without ensuring adequate landing space, do not improve accessibility. Instead, accessibility needs to be considered across the entire journey chain from the time of arrival at the transit node to boarding and alighting from the vehicle [33]. Currently, user-centred evaluation approaches are being increasingly emphasised. Evaluating the built environment is critical, as it has a nonlinear impact on bus usage by older adults and their mobility [38]. These approaches combine technical aspects with lived experiences for a better understanding of how individuals interact with infrastructure facilities and systems [23,39]. For example, Bertocci et al. and Frost et al. [40,41] demonstrate how ramp slope impacts safety during boarding and alighting. Park and Chowdhury [42] highlight that barriers extend beyond physical design and include service delivery and attitudinal issues. These studies suggest that accessibility cannot be solely evaluated on the availability of design elements. Instead, the functional interaction between the physical abilities of users and the design of infrastructure needs adequate consideration [23,43].

2.3. Accessibility Research in Asian and Indian Intermediate-City Contexts

While metropolitan hubs like Seoul [44–46], Kuala Lumpur, and Singapore [47] benefit from centralised funding for high-tech transit integration [48–57], intermediate cities like Udupi operate under fragmented, private sector models. This creates an empirical gap, where infrastructure evolves incrementally, haphazardly, and without the support of dedicated grants. Recent studies in intermediate Asian cities like Kampung Melayu, Indonesia [58] Solo City, Java, Indonesia [59] and suberbs of Jakarta and Kuala Lumpur [60] highlight a persistent implementation gap where existing transit nodes lack basic universal design features despite national policies.

In the Indian context, accessibility implementation in intermediate cities demonstrates regional variation. In Northern Indian cities like Jodhpur and Lucknow, studies prioritise macro-level mapping of physical barriers that lead to the isolation of PwLD [61]. In South India, cities like Mysuru have transitioned toward service-oriented inclusion. A benchmark example is the Dhwani Spanda project in Mysuru, which utilises the national

award-winning OnBoard assistive technology to enable visually impaired passengers to independently identify bus routes [62]. Review reveals that while public transport accessibility levels are high, functional usability for wheelchair users remains significantly low [63].

By synthesising these Asian and Indian perspectives, this study identifies aspects in the intermediate city of Udupi that have received limited scholarly attention [6]. These cities face distinct challenges, including incremental infrastructural growth, weaker enforcement of accessibility norms, and limited institutional capacity. Although national accessibility guidelines exist [40], implementation gaps persist, and awareness among users is limited [64]. The presence of policies does not necessarily translate into accessible design at the ground level. Furthermore, a significant methodological gap exists in the current literature. Meanwhile, advanced studies utilise machine learning-integrated global sensitivity analysis (GSA) [65] and multilevel statistical methods [66]. To model pedestrian satisfaction, these models are often decoupled from the lived experience of specific marginalised groups in data-poor environments. There is a lack of research that utilises a joint display synthesis [67] to explicitly map technical 'compliance failures' directly to the 'physiological strain' and 'user adaptation narratives' of PwLD. This study addresses this gap by presenting empirical evidence from Udupi, a representative intermediate Indian city. The study examines how 14 identified accessibility parameters mentioned in Table 2 manifest under real-world conditions. This research contributes detailed context-specific insights into bus infrastructure accessibility within a smaller but rapidly evolving urban setting. It integrates a rater-reliable physical audit with stakeholder narratives, moving beyond a binary checklist to evaluate the functional utility of the transit interface.

Table 2. Built environment accessibility parameters identified.

Sl. No.	Accessibility Factors	Accessibility Parameter
A.	Physical Infrastructure	1. Connectivity and Parking 2. Space Allowances and Levels 3. Surface Materials and Finishes 4. Lighting 5. Seating and Waiting Spaces 6. Ramp Slope and Accessibility 7. Sidewalks and Kerbs 8. Railings 9. Circulation and Movement Spaces
B.	Service-related Provisions	10. Safety and Security 11. Maintenance and Management 12. Sanitation and Plumbing Facilities 13. Human Resources
C.	Information Systems	14. Signages and Communication

2.4. Data Analysis in Built Environment Research

Currently, the use of computer-assisted qualitative data analysis software (CAQDAS) tools, such as ATLAS.ti-26, is gaining prominence in analysing complex qualitative data. Earlier studies have utilised thematic mapping for validation through the lived experiences of users [68,69]. This study utilises these advanced tools and techniques for data capture from multiple stakeholders and contexts. It is further synthesised to understand issues and concerns related to the accessibility of bus transport infrastructure.

3. Methodology

3.1. Research Design

This study, as illustrated in Figure 1, adopted a pragmatic, convergent, parallel, mixed-methods design. This framework ensured that quantitative spatial audit metrics and qualitative user narratives were not merely presented in parallel but were synthesised through a joint display. Following the methodology of Patella et al. [67], the synthesis allowed for the mapping of technical infrastructural deficits against real-world functional performance, creating a validated empirical baseline for transit interface resilience. It systematically mapped quantitative 'compliance scores' against qualitative 'user adaptation narratives,' ensuring that parameters were evaluated for functional utility rather than mere presence [70]. This specific process allowed for the identification of 'functional gaps' where infrastructure may be technically present but remains absent across selected transit interfaces in Udupi [71,72]. Integration of this data allowed the cross-verification of findings and helped to capture both the infrastructural conditions and the lived experiences of users [73,74]. The study was conducted adhering to national guidelines and institutional ethical approval. Informed consent was collected from all respondents before the commencement of data collection.

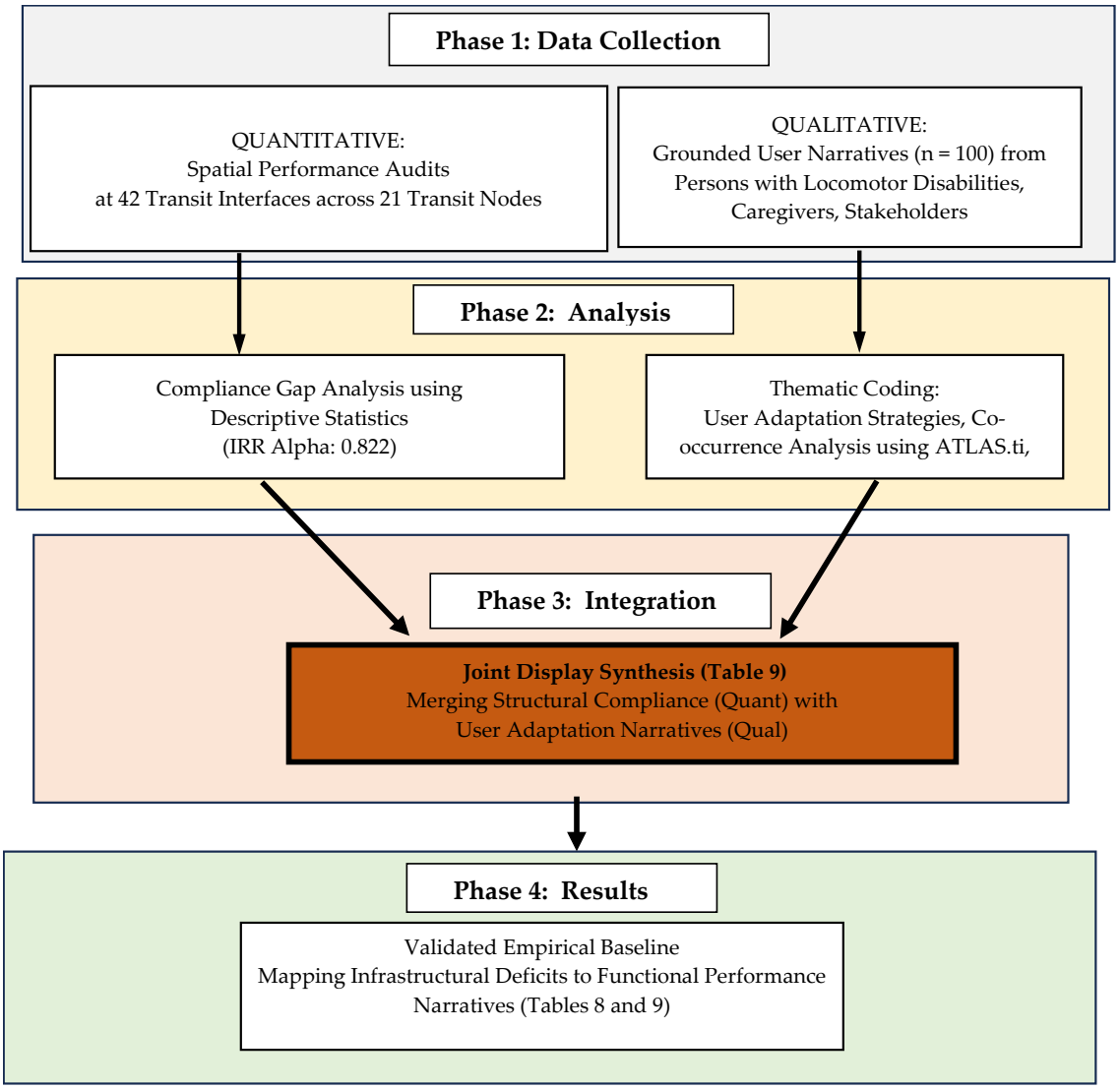


Figure 1. Research framework employing a convergent parallel mixed-methods design [67].

3.2. Evaluation Framework: Parameter Screening and Weighing Rationale

The 14 accessibility parameters identified in Section 2.3 were screened and selected based on the synthesis of Indian guidelines [7,75] and international benchmarks [76]. This dual screening ensured that the evaluation was grounded in the national legal mandate under the Rights of Persons with Disabilities (RPwD) Act (2016) [77], while remaining comparable to global best practices in universal design. The parameters were categorised into three dimensions—physical infrastructure, service provisions, and information systems—to represent the 'complete trip' experience. In this study, an equal weight model was adopted for the following reasons.

- Weakest link principle—For a person with a disability, a journey is only as accessible as its most restrictive point, e.g., a single in accessible barrier, like a lack of an accessible ramp, can render an otherwise compliant transit chain functionally unusable [78].
- Objective baseline for intermediate city context—By assigning equal weight to all identified parameters, the study avoided the subjective bias often found in expert-ranking methods like AHP, where certain aspects might be prioritised over others based on personal perceptions. Instead, an unweighted index provided a transparent, fair, and repeatable benchmark. Such an approach is suitable for intermediate cities like Udupi, where fundamental infrastructure gaps are widespread [79]. However, the study acknowledges that advanced methodologies, such as integrating machine learning with global sensitivity analysis [65] and multilevel statistical methods [66], are increasingly vital for modelling complex user satisfaction and transport acceptance in urbanising contexts.

This methodological choice ensured that the evaluation was a rigorous diagnostic tool rather than prioritised ranking, highlighting that every parameter is a critical requirement for achieving true universal accessibility.

3.3. Study Setting and Participants

Udupi (13.3409° N, 74.7421° E) has an approximate population of 125,000 persons, as per the census in 2011 [80]. It was selected as the case study due to its characteristics as a rapidly growing intermediate city with high bus transit dependence. The study was conducted on a 10.2 km East–West bus transit corridor, as shown in Figure 2, which was selected not only for its high passenger footfall but also for its role as the 'functional spine' of Udupi. This corridor serves as a representative microcosm of the urban and socioeconomic diversity typical of intermediate Indian cities. It uniquely connects three distinct urban typologies: the specialised healthcare and educational hub of Manipal from the Manipal Institute of Technology (MIT) transit node (origin), the high-density commercial and administrative core of Udupi (interchange), and the industrial port and tourist destination of Malpe (destination). Consequently, the corridor captures a wide spectrum of transit user behaviours and built environment challenges, making the audit findings indicative of systemic infrastructure gaps found throughout the city's primary transit network. This stretch includes 42 transit interfaces at 21 nodes, as detailed in Appendix A.

The selection of this specific corridor ensures 'empirical representativeness.' While it covers a distance of 10.2 km, it serves the transit needs of approximately 50,000 daily commuters in a city of less than 200,000, effectively capturing the transit experience of 25% of the total population. Furthermore, as an intermediate city that relies on a 90% share of private sector bus operators, Udupi represents a critical administrative typology in the Global South where centralised planning is often secondary to incremental, market-driven growth. The findings from this 'spine' are therefore generalisable to other intermediate Indian cities facing similar jurisdictional and funding vacuums.



Figure 2. Map of Udupi highlighting the 10.2 km bus corridor from MIT to Malpe Beach with Transit Nodes marked [81].

The average distance between the bus transit nodes on this stretch is 500 m. Although 42 transit interfaces are required to serve both sides of 21 nodes, only 14 transit interfaces exist, which is only 33% of the requirement. This leads to significant challenges not only for PwLD but also for the broader commuting population, especially during the four-month-long rainy season and harsh summer. These 42 transit interfaces were further studied through on-site observations. They were broadly classified into three categories based on the type of transit interface and availability of a roof shelter, a critical built environment element related to climatic considerations in Udupi. Udupi is a coastal city with a hot, humid tropical climate and a four-month-long monsoon rainy season.

Categories of bus transit interfaces on the identified stretch.

1. Bus terminals
2. Bus transit interfaces
    a. Transit interfaces with a roof
    b. Transit interfaces without a roof

Based on these broad categories, a total of 8 transit interfaces were selected from the total 42 interfaces (21 nodes × 2 transit interfaces on the north and south sides of the road = 42 transit interfaces). Further reasons for selecting these eight interfaces, covering all three categories mentioned above, are provided in Table 3. The selection utilised a stratified purposive sampling approach to represent three distinct urban typologies along the corridor: educational/healthcare (Manipal), commercial/administrative (Udupi Core), and industrial/tourism (Malpe). To ensure consistency and eliminate inter-site variability, the same two primary raters performed the technical audit of all 42 transit interfaces across the 10.2 km corridor of the 14 built environment parameters. Semi-structured interviews were also conducted with stakeholders at these locations, providing qualitative insights. These provided critical insights through first-hand experiences and concerns of individuals using these public facilities. They helped in gaining insights into participants' experiences and perspectives.

For the study, participant recruitment utilised a combination of intercept sampling at transit nodes and snowball sampling through local disability advocacy groups and governmental agencies to reach PwLD. Based on qualitative best practices, the final sample size (n = 100) was determined by the principle of thematic saturation. This threshold was operationalised as the point where three consecutive semi-structured interviews yielded no additional novel codes or emergent sub-themes pertaining to the 'compliance–resilience gap' or 'user adaptation narratives.' This stopping rule ensured that the qualitative findings were representative of the recurring systemic barriers faced by PwLD within the corridor, rather than being skewed by outlier experiences. The participant groups included:

- Persons with locomotor disabilities (n = 18);
- Caregivers and family members of PwLD (n = 12);
- General commuters (n = 60);
- Transportation administrators and service personnel (n = 10).

Table 3. Categories of bus transit interfaces on the identified route and reasons for the selection for in-depth observational studies.

Sl. No.	Transit Interface Category	Transit interface locations (Note—N, North; S, South side bus transit interface. If nothing is mentioned, it applies to both sides (N and S sides)	Selected locations where observational studies/site interviews were conducted	Reasons for the selection of a particular transit interface
A	**Bus terminals**	• Udupi City bus terminal • Malpe transit interface • Tiger Circle transit interface.	• Udupi City bus terminal. • Tiger Circle transit interface	Maximum passengers using as origin, destination, or interchange transit interface.
B	**Transit interfaces with a roof**			
B1.	**Bus transit interfaces with a roof**	• MIT transit interface • MJC transit interface • MGM transit interface • Kalsanka (N) • Adi Udupi Tax Office (N) • Kalmady • Kalmady Bridge (N)	• MIT North transit interface. • MIT South transit interface. • MGM College transit interface. • Kalmady Bridge (N)	Used by a large number of students, patients, and devotees. Used by a large number of students. Though it is a new transit interface, it is not much used.
B2	**Bus transit interfaces without a roof**	• Laxmindra Nagar Indrali • Sharda Mantapa • Kunjebettu • Kadiyali • Kalsanka (S) • Bannanje • Karavali • Adi Udupi • Adi Udupi Tax Office (S) • Pandubettu • Kalmady(N) • Koragajja • Kalmady Bridge (S) • Yeluru	• Indrali bus transit interface • Karavali Junction	Used by a large number of people to access the railway station. On Panvel—Kanyakumari National Highway—66. Used by a large number of travellers to access intercity buses.

This mix enabled a broader understanding of concerns from both users' and service providers' viewpoints. All participants provided informed consent before data collection, and their anonymity and confidentiality were strictly maintained throughout the study.

3.4. Data Collection Methods

Primary data collection was conducted using the following three complementary methods. The intent was to capture both the status of identified parameters and the lived experiences of the stakeholders.

3.4.1. Observational Assessments

Systematic on-site observations were conducted across all 42 transit interfaces. A structured checklist based on 14 identified accessibility parameters [24] guided the data collection. Physical measurements (e.g., ramp slopes and clear widths) were noted using standard tools. High-resolution photographic and video documentation supported field notes.

During these site visits, attention was given to how individuals with different mobility aids interacted with the environment. Data collection involved documenting the specific mobility aid used by individuals (e.g., manual/powered wheelchair, crutches, cane, and walker). Observations included difficulties faced in manoeuvring, transferring, boarding conditions, and negotiating level changes. This added a functional dimension to the assessment beyond regulatory compliance.

3.4.2. Semi-Structured Interviews

Semi-structured interviews (n = 70) were conducted with PwLD, caregivers, and transport personnel. Due to the low on-site presence of PwLD at transit interfaces, several interviews were conducted at the homes of respondents or via telephonic mode. Interviews were conducted with 16 individuals with locomotor disabilities and 12 caregivers and family members based on convenience. Interviews were also conducted at the bus transit interfaces with transport officials, bus conductors, drivers, and other related staff to understand their perspectives. The participants were assigned unique identifiers (P01–P70) to maintain anonymity while ensuring traceability of narratives. The interviews explored daily travel issues, concerns, coping strategies, perceived safety, and expectations from public bus transport infrastructure. Interviews were conducted in multiple local languages—Kannada, Hindi, and English—depending on participant preference and ranged between 20 and 60 min.

3.4.3. Stakeholder Surveys

Data were collected through semi-structured interviews and surveys (n = 100) conducted with a diverse group of stakeholders, including PwLD, primary caregivers, commuters, city transport officials, staff, and local bus operators. Surveys were distributed in both online and paper formats to a broad group of stakeholders. Thirty completed responses were received. Data collection was structured around four primary functional domains: physical access, comfort, information clarity, and overall usability. These domains consolidated the 14 technical parameters into user-centric categories to ensure data reliability across a diverse participant pool. This multi-stakeholder approach ensured that the assessment accounted for both user experience and operational feasibility. The details of stakeholders and the method of data collection are presented in Table 4.

Table 4. Stakeholder details and method of data collection.

Sl. No.	Stakeholder	Semi-Structured Interviews		Surveys		Total
		Male	Female	Male	Female	
1	Persons with locomotor disabilities	9	7	1	1	18
2	Caregivers and family members of PwLD	3	7	1	1	12
3	General commuters	22	16	16	6	60
4	Transportation administrators and service personnel	4	2	3	1	10
	Total	38	32	21	9	100
	Grand Total	70		30		

3.5. Data Analysis

The collected data were analysed using a convergent synthesis approach by integrating both quantitative and qualitative findings [73,74].

3.5.1. Quantitative Analysis

Quantitative data were analysed using descriptive statistics in MS Excel. The observed measurements and readings were compared with national and international accessibility guidelines and standards.

3.5.2. Qualitative Analysis

Qualitative data from interview transcripts and field notes were coded in ATLAS.ti 25 using a hybrid approach for systematic thematic analysis [82,83]. Initial codes were derived from the identified accessibility parameters, while additional themes emerged inductively from narratives of the stakeholders. This process facilitated the identification of recurring themes related to aspects like infrastructural inadequacies, service delivery gaps, safety concerns, information accessibility barriers, and ingenious user adaptation strategies. Co-occurrence analysis was utilised to map the link between environmental aspects (e.g., high bus footboard heights) and user responses (e.g., anxiety and social dependency).

3.5.3. Inter-Rater Reliability (IRR)

To strengthen analytical reliability, an inter-rater reliability (IRR) test was conducted using a template as per Appendix B. To ensure scientific objectivity and capture a diverse range of perspectives, the audit was conducted by a transdisciplinary team of five trained evaluators independently. This panel included two architecture graduates, one university student, one senior citizen, and one civil engineering faculty. All evaluators were regular users of the Udupi bus transport system and underwent a standardised calibration workshop to synchronise scoring against the 14-parameter protocol at 8 transit interfaces. This diverse mix allowed the study to capture both technical design compliance and the functional lived experience of different demographic cohorts. A total of 112 ($14 \times 8 = 112$) parameters were assessed. The collected data were coded, rated, and further analysed. The following two metrics were calculated.

(A) Simple pairwise agreement (P_o)—This was used to determine raw consistency across the 5-point Likert scale used in the study.

$$\text{Agreement } \% = \frac{\text{Total Agreeing Pairs}}{\text{Total Possible Pairs}} \times 100$$

The observed value was 80.27%, indicating good preliminary consistency.

(B) Krippendorff's alpha (α)—This coefficient was selected for its robustness and suitability for multiple raters and ordinal (Likert's scale) data for chance agreement [37,84].

$$\propto = 1 - \frac{D_o}{D_e}$$

where, D_o = observed disagreement and D_e = disagreement expected by chance.

The alpha value was calculated using the irr package in RStudio software version 2026.04.0+526. The calculated value of 0.822, which was obtained after analysis, signified strong agreement among raters [6]. The results of the inter-rater reliability (IRR) test are summarised in Table 5.

Table 5. Validated observational audit through inter-rater reliability (IRR).

Metric	Observed Value	Interpretation of Observation [85]
Number of raters (*k*)	5	Multiple rater design
Units of analysis (*N*)	112	14 parameters × 8 selected locations
Simple pairwise agreement	80.27%	Good preliminary consistency
Krippendorff's alpha (∝)		Near perfect agreement

3.5.4. Mixed-Methods Integration

The study utilised a convergent parallel mixed-methods design, where integration was achieved through the joint display approach of Patella et al. [67]. The process involved comparison of quantitative 'compliance status' derived from the site audit of 42 transit interfaces and qualitative 'user adaptation narratives' extracted from semi-structured stakeholder interviews. Quantitative descriptive findings were integrated with rich qualitative themes through a convergent synthesis approach [67,71,73] at the interpretation stage. As illustrated in Phase 3 of Figure 1, this integration allowed for triangulation for a comprehensive understanding of why technically present features may still fail to provide real-world accessibility to PwLD. This integration helped in the identification of areas of convergence and divergence. Analysis of data collected based on parameters of the study, supported by observational assessments at various locations, was a crucial component of this integration. By mapping the datasets into a unified matrix, the study moves beyond a binary checklist to evaluate the functional performance of the transit interfaces. This method ensured that the meta inferences were grounded in both empirical measurements and lived experiences of PwLD.

3.5.5. Statistical Analysis

To evaluate the compliance gap (H1), a Pearson's chi-square (χ^2) goodness-of-fit test was performed on the binary physical audit data (n = 42). The observed frequency of 'present' vs. 'absent' features was tested against a theoretical benchmark (50% expected compliance) to determine if the observed deficits were statistically significant. This 50% benchmark represents a "hypothetical parity" testing whether the infrastructure is compliant at a rate better than random chance.

To test H2, a one-sample *t*-test was conducted on the "overall usability" perception ratings (n = 100). The mean perception score was compared against a test value of 3.0 representing 'moderate accessibility' to determine if user dissatisfaction was statistically significant. Data as represented in Table 6 were analysed using MS Excel, using a significance level set at $p < 0.05$.

Table 6. Compliance status and inferential analysis of accessibility parameters (n = 42) * Note—χ^2 tested against equality of distribution (Expected = 21 Present, 21 Absent). (* $p < 0.05$, *** $p < 0.001$).

	Domain and Parameter	Present (n)	Absent (n)	Compliance Rate (%)	(χ^2) Value	*p*-Value	Remarks
I.	Physical Infrastructure						
1.	Connectivity and Parking	10	32	24%	11.52	0.0007 ***	90% parking deficit; systemic exclusion from first-mile access
2.	Space Allowance and Levels	14	28	33%	4.67	0.0307 *	67% lack shelter; overcrowding due to vertical boarding gaps
3.	Surface Materials and Finishes	9	33	21%	13.71	0.0002 ***	79% lack slip-resistance; total absence of tactile markings

Table 6. *Cont.*

	Domain and Parameter	Present (n)	Absent (n)	Compliance Rate (%)	(χ^2) Value	*p*-Value	Remarks
4.	Lighting	8	34	19%	16.09	<0.0001 ***	High dependence on streetlights; creation of unsafe dark zones
5.	Seating and Waiting Spaces	8	34	19%	16.09	<0.0001 ***	Total absence of designated wheelchair waiting zones
6.	Ramp Slope and Accessibility	1	41	2%	38.09	<0.0001 ***	Functional failure point; 98% absence of ramps
7.	Sidewalks and Kerbs	2	40	5%	34.38	<0.0001 ***	Impassable vertical barriers; 95% lack of kerb cuts
8.	Railings	6	36	14%	21.43	<0.0001 ***	Stability risk: railings are discontinuous or broken
9.	Circulation and Movement Spaces	3	39	7%	30.86	<0.0001 ***	Spatial conflict; absence of demarcated movement zones
II.	Service Provisions						
10.	Safety and Security	0	42	0%	42.00	<0.0001 ***	Functional failure point: no dedicated safety measures
11.	Maintenance and Management	3	39	7%	30.86	<0.0001 ***	Neglect renders existing accessible features unusable
12.	Sanitation and Plumbing Facilities	3	39	7%	30.86	<0.0001 ***	93% absence of accessible toilets; high physiological stress
13.	Human Resources	0	42	0%	42.00	<0.0001 ***	Lack of trained personnel for regulated bus boarding
III.	Information Systems						
14.	Signages and Communication	0	42	0%	42.00	<0.0001 ***	Functional failure point: total information vacuum

4. Results

This section presents the empirical findings from the observational assessments, interviews, and stakeholder surveys conducted across 42 transit interfaces across 21 transit nodes in Udupi. The results indicate substantial accessibility gaps across physical infrastructure, services, and information systems. The findings have been organised under the three broad domains of the accessibility framework—infrastructure, services, and information.

4.1. Participant Profile

The study engaged a diverse group of stakeholders. The demographic profile of participants (N = 100) is given in Figure 3.

The respondents of the study were selected based on the following inclusion and exclusion criteria

(A) Inclusion Criteria

- Users of Udupi intra-city bus transit interfaces;
- Persons with locomotor disabilities who are natives or visitors of Udupi;
- Caregivers for PwLD who are natives or visitors to Udupi;
- Citizens facing temporal disabilities due to health issues and age who are likely to use public bus transportation facilities for accessing medical facilities and for other purposes;

- Commuters using Udupi transit interfaces regularly or occasionally, viz., senior citizens, students, tourists, service goers, traders, labourers, patients/patient relatives, and the general public;
- Policymakers, government officials, and persons associated with the local bus transportation system.

(B) Exclusion Criteria—People who were not using and not likely to use Udupi bus transportation facilities were not included in the study.

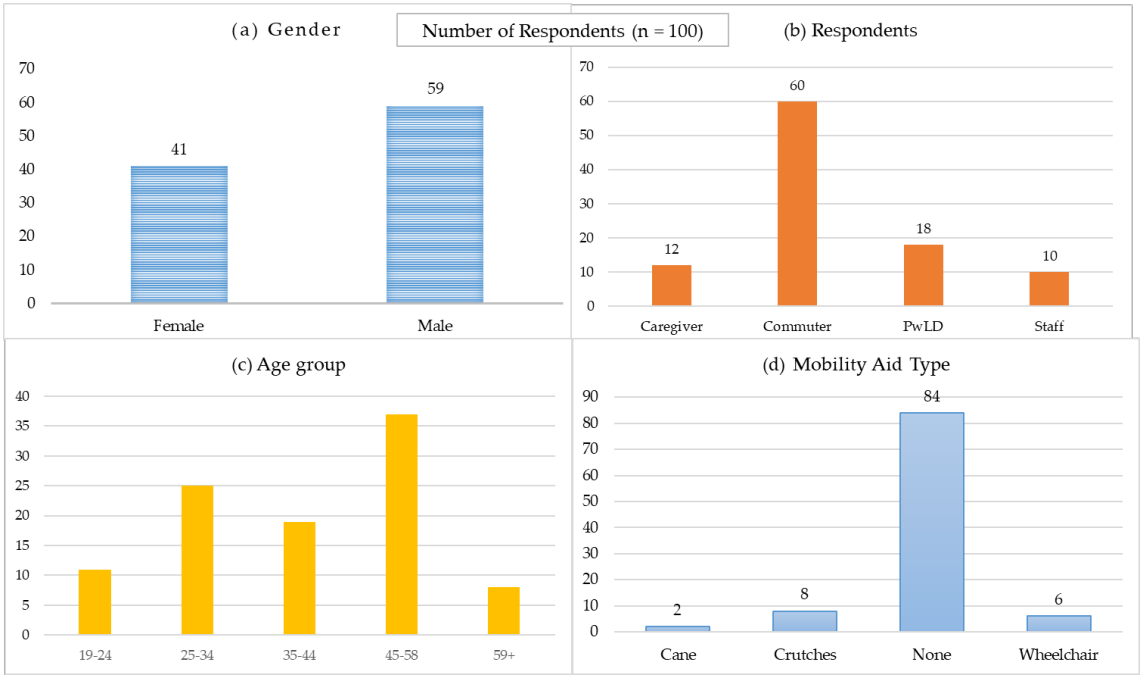


Figure 3. Demographic profile of study participants (n = 100). (**a**) Gender distribution; (**b**) distribution of respondent categories; (**c**) age distribution of participants; (**d**) types of mobility aids used by respondents.

4.2. Physical Infrastructure

Observational assessments across 42 transit interfaces revealed a stark "compliance–resilience gap" as illustrated in Figures 4 and 5. The lived experiences of PwLD validated the technical audits (Table 6). Based on repeated field visits to these transit interfaces, it was observed that though accessibility features are conceptually present in design documentation, they are poorly implemented and inadequately maintained in the built reality. A comprehensive compliance summary of the 42 audited transit interfaces is presented in Table 6.

1. Connectivity and parking: Connectivity emerged as a major barrier. In total, 80% of surveyed stakeholders identified inadequate access and parking near the bus transit interfaces as a primary concern. Observational data showed haphazard bus parking and private vehicles blocking access, severely hindering seamless transitions from surrounding areas to transit interfaces. Accessing the transit interface was challenging in 32 out of 42 (76%) interfaces, whereas parking was a critical issue in 38 out of 42 (90%) transit interfaces. User P01 noted that even newly constructed interfaces like the MIT transit interface are rendered unusable because of "crowding of private vehicles blocks entry," forcing users to hire expensive private modes of transport.
2. Space allowances and levels: Out of 42 transit interfaces studied, only 14 (33%) had a roof covering. The clear width at boarding areas was measured between 500 and 900 mm, below the minimum 1200 mm requirement. This resulted in failure to accommodate wheelchair turning radii due to a lack of space, uneven flooring levels,

and poor design. A critical vertical gap existed between the bus footboard and the interface flooring. Few buses had a footboard height of more than 400 mm, making them inaccessible to wheelchair users. Accessing these high-footboard buses was challenging for crutch users, cane users, senior citizens, patients, small children, expecting mothers, and persons with mobility issues (P09). Crutch and polio-affected users were physically incapable of boarding without being "lifted like a child" (P01). At interfaces like Malpe, during peak hours, vendor encroachment, private vehicles, and crowding further reduced effective circulation space by an estimated 35%, making wheelchair passage physically impossible (P04). This resulted in systemic congestion and unregulated transit flow, precipitating chaotic conditions that significantly compromise user safety.

3. Surface materials and finishes: Slip-resistant surfaces were present at only 9 transit interfaces (21%). Tactile guidance and surface markings were not present at any locations. Uneven pavements, cracks, broken tiles, debris, leftover construction, and waste materials were observed at 15 out of 42 (36%) transit interfaces. These factors contributed to "fear of falling" as one of the prominent observations. This was noted in 85% of elderly respondents as a critical aspect. The use of inappropriate materials was a major failure point. At Kalmady Bridge, users reported the use of vitrified tiles, which became "extremely slippery with the slightest rain" (P19). This "engineering failure" created a "fear of falling" among older adults, particularly during Udupi's four-month-long rainy season.
4. Lighting: Only 8 (19%) transit interfaces had functional lighting, which was not inadequate and uneven, creating dark spots and shadows. Most transit interfaces, including non-roofed ones, depended on streetlights for required lighting. At the Madhava Kripa School interface, a mobility-challenged person emphasised that dim lighting prevented users from judging kerb heights, leading to near-fall incidents and a "constant state of high anxiety" especially after sunset (P13).
5. Seating and waiting spaces: Only 14 out of 42 shelters (33%) had a roof covering, out of which only 8 transit interfaces (19%) provided some form of seating. Crucially, none met accessibility standards for height, depth, backrest, or armrest provision. Designated spaces for wheelchair users were absent. Waiting for long periods caused severe physical strain. One crutch user lamented, at the MGM College interface, that there was no proper place for seating. Lack of backrests forced users with chronic pain to "lean against railings," leading to "legs trembling with physical strain." Sometimes this user was forced to take an autorickshaw, although they were more than 10 times more expensive than bus fare, or had to depend on friends and family to commute (P11). Due to a lack of waiting space, some caregivers were forced to carry their own chairs to the interface for the comfort of persons with mobility concerns (P17).
6. Ramp slope and accessibility: Only one of 42 transit interfaces (2%) had a ramp, but the slope was steep (1:8.5), significantly exceeding standards. A wheelchair user reported the ramp was so steep that their relative needed to push the wheelchair from behind every time (P02). All other places lacked ramps. Interviewed PwLD, particularly wheelchair users (n = 6) and crutch users (n = 8), consistently reported lack of ramps as one of the biggest deterrents in accessing bus transit interfaces apart from the design of buses, especially the small entries of existing buses. Lack of ramps made their travel difficult, unsafe, and necessitated external assistance. This created a physical exclusion zone for manual wheelchair users without assistance. One wheelchair user mentioned, "Though I am ready to use bus services, I am forced not to use them due to a lack of ramps, and also I cannot enter existing buses that do not have adequate space for entry of a wheelchair or a place to keep the wheelchair after boarding. I am hoping

that ramps will be provided as well as low-floor buses with adequate door width for entry of my wheelchair in future, and then I will surely use bus transport."

7. Sidewalks and kerbs: Kerb cuts were mostly absent or, where present, they poorly transitioned (e.g., level difference of more than 25 mm), creating impassable vertical barriers for most mobility aids and forcing PwLD to seek help. Accessible sidewalks and kerbs were found at only 2 out of 42 (5%) of transit interfaces.
8. Railings: Handrails were present at only 6 out of 42 (14%) transit interfaces. Where present, they were broken, poorly maintained, or not continuous, impacting stability. One cane user mentioned, "Without a railing, I feel very uncomfortable. It worries me, and I depend on others for help, which I don't like."
9. Circulation and movement spaces: At 39 out of 42 (93%) of transit interfaces studied, there was a lack of adequate, well-defined, and demarcated space for circulation and waiting for commuters and for persons with mobility aids or using wheelchairs. During peak hours, intermixing of people, luggage, goods, vehicles, vendor encroachment, and crowding further reduced the effective circulation space by an estimated 35%. This resulted in systemic congestion and unregulated transit flow, precipitating chaotic conditions that significantly compromise user safety. One crutch user stated, "I am afraid I may trip and fall due to the crowd and the dynamic movement of vehicles and buses." (P15)



Figure 4. Illustrative evidence of built environment accessibility barriers and functional performance gaps at transit interfaces.

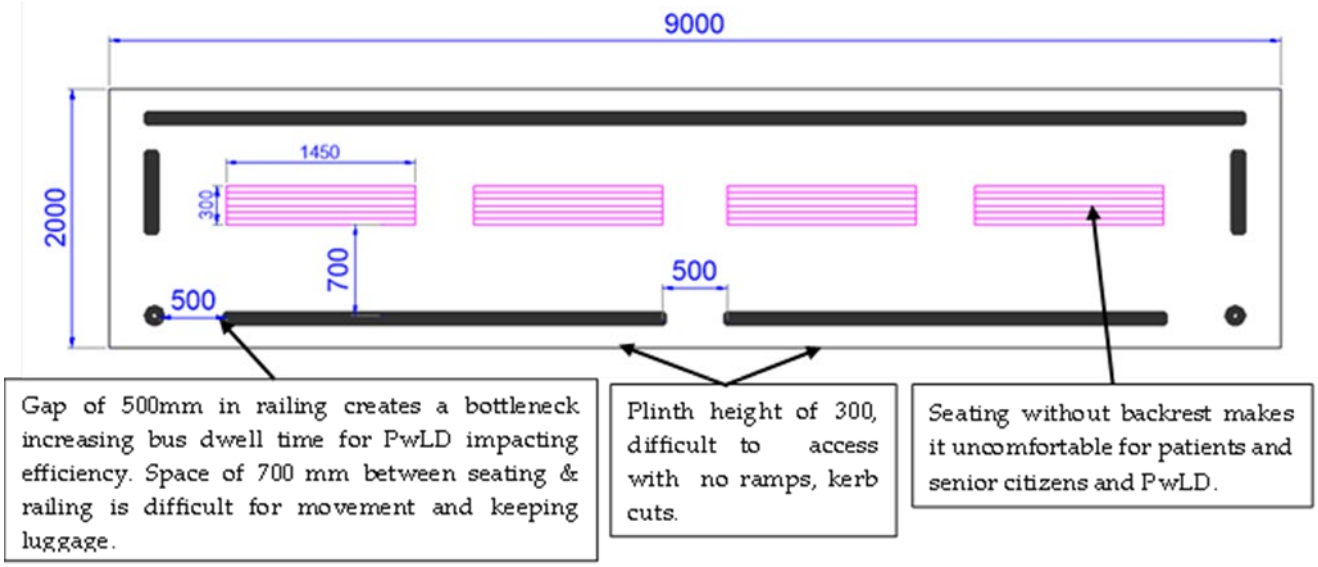


Figure 5. Plan of a typical covered transit interface in Udupi, highlighting built environmental issues for PwLD (Source—Author) (All dimensions are in mm).

4.3. Service-Related Provisions

1. Safety and security: There was no provision of dedicated safety personnel or measures at any transit interface. Transport staff members were available occasionally. Traffic police personnel were present at important junctions. A few users voiced a preference for certain known staff members for travel decisions, which impacted their travel time. If a known staff member was not available, either the user was delayed or they decided against travel due to anxiety and safety concerns (P20). Such travellers trusted individuals more than the system.
2. Maintenance and management: Lack of maintenance or inadequate maintenance was observed in 39 out of 42 (93%) of audited interfaces. Observations documented broken or defective handrails at 6 out of 42 transit interfaces (14%), dust and debris accumulation at 15 out of 42 (36%) transit interfaces, and non-functional lighting at 6 out of 42 transit interfaces (14%). This neglect rendered even existing accessible features unusable over time. Maintenance was a critical mobility barrier. At Udupi transit interfaces, users reported that "garbage gets stuck in wheelchair wheels" (P02). This neglect can render infrastructure non-resilient and inaccessible.
3. Sanitation and plumbing facilities: Accessible toilet facilities and drinking water points were absent. They were partially observed only at three transit interfaces (7%) but were not accessible to wheelchair users due to the lack of a ramp to negotiate the floor level difference and an inadequate 900 mm wide door opening. They also lacked basic features like grab bars and adequate manoeuvring space for PwLD. These facilities were essential at locations like Karavali Junction and the Indrali transit interface, which had high passenger footfall and passengers travelling from outstations due to their location near the National Highway and the railway station, respectively. A few respondents reported not drinking water before travelling due to the lack of accessible washrooms (P37).
4. Human resources: Due to the prevalence of private sector operators, there was a notable absence of formal administrative personnel at all locations other than bus conductors and drivers. Due to intensive competition to maximise the number of passengers, the basic requirements of needy passengers were often overlooked. Buses were often operated aggressively, not halting at designated interfaces. None of the transportation staff who were interviewed reported receiving disability awareness

training. One senior citizen noted, "Few bus staff are helpful, but others seem annoyed when I take time to board or deboard. Many times, buses do not park near transit interfaces and by the time you rush to catch them, they speed away. It leads to anxiety and stress." A few people reported a lack of independence since staff and other people ignored them, and they felt like small children dependent on others (P01, P15). This highlights a critical need for formalised sensitisation training and management of transport staff and measures to facilitate vulnerable passengers.

4.4. Information Systems—Signages and Communication

The study also identified significant gaps in service provision and information accessibility in terms of signage and communication. Audiovisual communication facilities, which are essential in the management of public transportation and energy response, were not available at any locations. Few passengers (10%) were aware of a transport app through which they could track buses. But since not all buses were equipped with GPS trackers, tracking was difficult. Most passengers were seen asking other passengers about bus availability, bus routes, etc. In the words of one passenger, this lack of information forces him to "beg for information" from random strangers (P24). On average, there was one bus every 10 min on this route, which compensated for the lack of timetable and bus route information at these transit interfaces.

The systematic inventory of the 42 audited transit interfaces revealed a prevalent compliance gap, as mentioned in Table 6.

The inferential analysis confirmed H1, revealing that the absence of accessible infrastructure was statistically significant across all 14 evaluated parameters ($p < 0.05$). Critical barriers, including ramp accessibility (P6), safety measures (P10), and information systems (P14), showed extreme divergence from the minimal compliance benchmark ($\chi^2 \geq 38.09$, $p < 0.001$). These results provide rigorous empirical evidence of a systemic, rather than incidental, failure in the design and implementation of the urban transit interface in Udupi.

As represented in Figure 6, parameters such as safety and security, human resources, and signages and communication showed a 0% compliance rate. Ramps were absent in over 98% of the transit interfaces, while sidewalks and kerbs were not available in 95% of transit interfaces.

Observational studies were conducted at all 42 transit interfaces across 21 transit nodes, but more in-depth studies were undertaken at 8 selected transit interfaces. Of these, except for Indrali and Karavali Junction, the other bus transit interfaces had a roof. The inter-rate reliability test (IRR), as detailed in Section 3.4.3, was conducted at these 8 transit interfaces. A summary of the study of these 8 transit interfaces on the identified 14 parameters is presented in Table 7.

Table 7. Status of facilities at eight selected transit interfaces, where observational studies and site interviews were conducted.

Sl. No.	Parameter of Study	Identified Eight Transit Interfaces for In-Depth Observational and IRR Study.							
		Udupi City (Terminus)	Tiger Circle (Interchange)	MIT North (Intermediate)	MIT South (Intermediate)	MGM (Intermediate)	Kalmady (Intermediate)	Indrali (Intermediate)	Karavali (Intermediate)
1	Connectivity and Parking	PC	PC	PC	PC	NC	NC	PC	PC
2	Space Allowances and Levels	NC	NC	NC	NC	NC	PC	NC	NC
3	Surface Materials and Finishes	NC	NC	C	C	NC	C	NC	NC
4	Lighting	PC	PC	C	PC	NC	NC	NC	NC

Table 7. *Cont.*

Sl. No.	Parameter of Study	Identified Eight Transit Interfaces for In-Depth Observational and IRR Study.							
		Udupi City (Terminus)	Tiger Circle (Interchange)	MIT North (Intermediate)	MIT South (Intermediate)	MGM (Intermediate)	Kalmady (Intermediate)	Indrali (Intermediate)	Karavali (Intermediate)
5	Seating and Waiting spaces	NC	NC	C	PC	NC	PC	NC	NC
6	Ramp Slope and Accessibility	NC	NC	NC	NC	NC	NC	NC	NC
7	Sidewalks and Kerbs	NC	NC	NC	NC	NC	NC	NC	NC
8	Railings	PC	PC	PC	PC	NC	PC	NC	NC
9	Circulation and Movement Spaces	NC	PC	PC	C	PC	PC	NC	NC
10	Safety and Security	PC	NC	NC	NC	NC	NC	NC	NC
11	Maintenance and Management	NC	NC	C	C	NC	C	NC	NC
12	Sanitation and Plumbing Facilities	PC	PC	NC	NC	NC	NC	NC	NC
13	Human Resources	PC	PC	NC	NC	NC	NC	NC	NC
14	Signages and Communication	NC	NC	NC	NC	NC	NC	NC	NC

Note: Legend for Table 7. C (Compliant): Feature fully meets national and international accessibility standards and is functional for independent use. PC (Partially Compliant): Feature is present but possesses significant barriers, poor maintenance, or limited usability for PwLD. NC (Non-Compliant): Feature is absent, dangerous, entirely, or entirely unusable for persons with locomotor disabilities (PwLD).

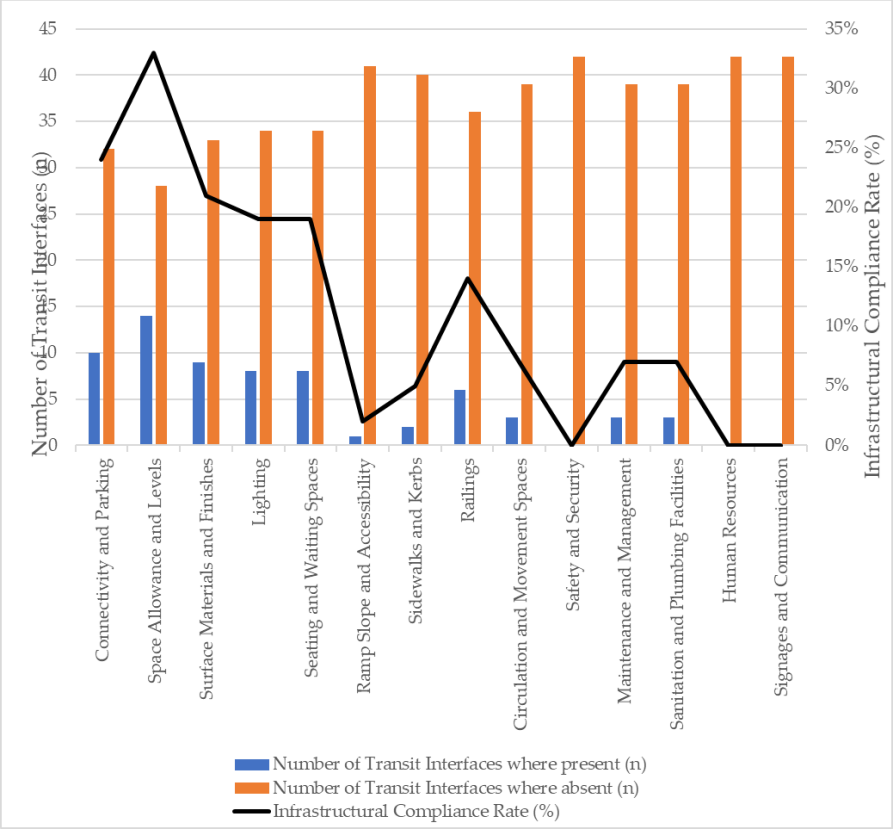


Figure 6. Comparative analysis of infrastructural compliance across 42 audited transit interfaces in Udupi. The grey line indicates the significantly low compliance rate for critical parameters such as ramps, safety and security, human resources, and signages and communication.

4.5. User Adaptation Strategies & Physical Abilities Context

Qualitative coding identified high frequencies of "anxiety" and "compensatory behaviours." Many users reported avoiding travel by buses due to surface hazards and preferring travel by specific company buses due to their "helpful" drivers and conductors. Participants demonstrated remarkable resilience and ingenious adaptation strategies in response to the challenging environment. An individual with mobility concerns mentioned, "I've noted bus timings and ask my family and friends to wait till the bus arrives so that I can wait in their four-wheelers due to a lack of roof shelter and waiting facility at the bus transit interface." Another person mentioned, "I call my family members before I reach the bus transit interface, so they come and pick me, and I don't have to wait in rain or sun." Another senior citizen, a retired banker, mentioned, "Whenever I need to travel, I plan only during off-peak hours in the afternoon when there's less crowd. It's not always convenient, especially during the summer, but it's safer." These strategies underscore the inadequacy of the infrastructure and the personal burden placed on users.

The detailed integration of data on respondents' physical abilities with observed infrastructural barriers provided crucial functional insights. For example, the clear width at boarding areas was observed to be 500 to 900 mm, which was far shorted than the standard 1200 mm required for wheelchair users. The wheelchair users who were interviewed clearly mentioned that the lack of infrastructure, services, and support systems at bus transit interfaces deterred them from using public transport.

4.6. Citizen Perception and Safety Analysis (Qualitative Insights)

User feedback through interviews and surveys was processed through ATLAS.ti software for qualitative analysis. The study revealed the following findings, which reinforced observational data:

- Eighty percent of the users identified physical infrastructure as the primary barrier;
- In total, 90% acknowledged difficulties faced by PwD in the transit interfaces;
- Only 12% rated existing accessibility provisions as adequate;
- In total, 92% supported increased investment in accessibility improvements;
- Perception of safety was heavily influenced by adequate lighting and staff assistance. This corroborated the findings in Riobamba, Ecuador [86], where 68% of users perceived low safety at transit interfaces that lacked surveillance, illumination, shelter, signage, and inclusive features, suggesting a global trend where infrastructural neglect directly compromises the safety of vulnerable transit users. These results demonstrate broad recognition of accessibility gaps among stakeholders. Beyond descriptive percentages, a one-sample *t*-test was performed to determine the significance of user dissatisfaction. The results indicated that the mean accessibility rating (mean = 1.55, $SD = 0.69$) was statistically significantly lower than the neutral threshold of 3.0 ($t(99) = -21.10$, $p < 0.001$). This confirmed that stakeholders did not merely perceive the system as 'sub-optimal' but as statistically 'inaccessible,' providing a rigorous quantitative basis for the high frequency of 'anxiety' and 'compensatory behaviours' identified in the qualitative coding. To validate the functional impact of the built environment on user experience, a code co-occurrence analysis was performed using ATLAS.ti Web. The qualitative co-occurrence matrix presented as Table 8 aligned with the physical compliance deficits shown in Figure 6, confirming that the parameters with the lowest physical compliance were also those linked to the highest levels of physiological strain in user narratives. The results demonstrated a significant thematic overlap between morphological deficits and user strain and anxiety. For example, 'seating and waiting spaces' showed the highest co-occurrence with physiological strain (10), reflecting severe fatigue experienced by users in the present transit infras-

tructure. Similarly, 'ramps and footboard' were strongly linked to 'forced dependency' (6), empirically validating the built environmental issues impacting the mobility of individuals. The co-occurrence matrix provided a robust statistical validation for the qualitative narratives, indicating that built environmental issues are the primary drivers of social exclusion of PwLD in the study area.

Table 8. Integrated matrix of physical barriers and physiological stress responses. Note—Darker cell shading (green/yellow) indicates a higher frequency of thematic co-occurrence in participant narratives.

Code Co-Occurrence Analysis	Adaptation: Forced Dependency	Adaptation: Temporal Displacement	Governance: Monitoring Gap	Governance: Safety and Security	Impact: Physiological Strain	Impact: Psychological Anxiety and Stress
Barrier: Connectivity and Parking	3	2	4	4	6	6
Barrier: Space Allowances and Levels	5	4	3	2	6	5
Barrier: Surface Materials and Finishes	3	2	2	2	8	4
Barrier: Lighting	3	3	2	2	4	4
Barrier: Seating and Waiting Spaces	6	4	3	4	10	7
Barrier: Ramp Slope and Accessibility	8	4	4	4	9	6
Barrier: Sidewalks and Kerbs	2	2	3	3	3	3
Barrier: Railings	1	1	3	1	2	2
Barrier: Circulation and Movement Spaces	6	4	3	4	10	7
Barrier: Safety and Security	8	6	10	10	11	9
Barrier: Maintenance and Management	4	3	5	5	8	7
Barrier: Sanitation and Plumbing Facilities	5	3	2	1	3	2
Barrier: Human Resources	6	5	4	5	6	7
Barrier: Signages and Communication	8	3	5	4	6	8

4.7. Integrated Synthesis: Bridging Infrastructural Deficits and User Narratives

Based on the convergent parallel design outlined in the research framework (Figure 1), a joint display analysis was conducted to triangulate quantitative compliance gaps with grounded qualitative narratives. As advocated by Patella et al. [67], this synthesis identified 'functional failure points'—areas where technical non-compliance directly translated into systemic exclusion or hazardous user adaptation. Based on the spatial metrics in Table 6 and user stress responses in Table 8, this section provides an integrated synthesis via joint display analysis, presented in Table 9. It maps the validated empirical baseline against the lived experiences of persons with locomotor disabilities (PwLD), highlighting the compliance–resilience gap. This mapping identified that the most critical functional failure points occurred where low physical compliance (e.g., P6, P10, P13, and P14) overlapped with high psychological and physiological user strain.

The joint display revealed that while some transit interfaces had a few accessibility features, the lack of standardised availability rendered them functionally non-resilient. This synthesis confirmed that compliant built environmental features are a prerequisite to advanced digital smart interventions. The results supported H1, confirming through χ^2 goodness-of-fit testing that a significant and systemic gap exists between regulatory intent and built reality ($p < 0.05$). This validated the proposed audit tool as a stable, objective benchmark for assessing built environment variables. Furthermore, H2 was confirmed through both qualitative thematic co-occurrence and inferential *t*-testing, which demonstrated that user perception of accessibility was statistically below satisfactory levels

($p < 0.05$). This dual-layer validation proved that built environmental barriers are the primary drivers of social exclusion and 'forced dependency' within the study area.

Table 9. Joint display synthesis: mapping audit compliance and user narratives functional performance impact.

Parameter ID.	Strategic Parameter	Quantitative Audit Result (Compliance %)	Qualitative User Narrative (Lived Experience)	Integrated Functional Performance Impact
P1	Connectivity and Parking	24%	"I cannot access it (MIT stop) due to the crowding of private vehicles. I am forced to hire private taxis, which are costly." (P01)	Economic Penalty: Forced reliance on costly private transport.
P2	Space Allowance and Levels	33%	"The bus footboard is very high. . . someone has to lift me (each time)." (P09)	Vertical Barrier: Erosion of user autonomy, dignity and forced dependency.
P3	Surface Materials and Finishes	21%	"They have used vitrified tiles which get slippery with the slightest of rains." (P19)	Design Negligence: High-risk materials increase the chance of falls and injuries.
P4	Lighting	19%	"Lighting at Madhava Kripa is so dim. . . I can't judge the height of the kerb. I nearly tripped once." (P13)	Design Failure: Navigational anxiety spikes after sunset if the lighting is not adequate due to the creation of dark spots and shadows.
P5	Seating and Waiting Spaces	19%	"I have to carry my mother's small chair to the stop because there is no place for her to sit." (P17)	Infrastructural inadequacy: Users are forced to compensate for the lack of infrastructure.
P6	Ramp Slope and Accessibility	2%	"The ramp (at the City Bus Terminal) is too steep, my relative has to push the wheelchair from behind every time." (P02)	Functional Failure Point: Deceptive access leading to physical exclusion and forced dependency.
P7	Sidewalks and Kerbs	5%	"Drivers do not stop near the bus stop. . .. . . they stop in the middle of the road where I can't reach." (P20)	Operational Barrier: Lack of kerb-side boarding protocols and staff sensitivity.
P8	Railings	14%	"There are no grab rails to help me steady myself when the crowd pushes." (P15)	Stability Risk: Crowding leads to a high risk of physical injury.
P9	Circulation and Movement Spaces	7%	"Vendors block the narrow paths (at Malpe Bus Stand). . . a wheelchair simply cannot pass through." (P04)	Spatial Conflict: Encroachment renders interfaces inaccessible.
P10	Safety and Security	0%	"I only board buses of certain specific drivers. . . if I see a different driver, I get anxious and don't board the bus. I miss many buses and get delayed, or sometimes I am forced to cancel travelling." (P20)	Functional Failure Point Systemic Neglect: Safety and trust rely on individuals rather than the system.
P11	Maintenance and Management	7%	"Garbage gets stuck in wheels (at City Terminal) and makes it difficult to move." (P02)	Maintenance-Mobility Link: Poor maintenance of infrastructure adversely impacts mobility.
P12	Sanitation and Plumbing Facilities	7%	"I stop drinking water before travelling because I cannot use the available washrooms." (P37)	Physiological stress and dignity are compromised due to a lack of accessible toilets.
P13	Human Resources	0%	"The general public ignore disabled people. . . I feel like a child and have no independence." (P01, P15)	Functional Failure Point: Social Exclusion and Loss of Independent Mobility.
P14	Signages and Communication	0%	"There is no audio nor displays. . . I feel like I beg to strangers for information about buses, routes and timings." (P24)	Functional Failure Point: Total informational exclusion and forced dependency.

Hypothesis Validation Summary

Based on the integrated analysis, both research hypotheses are supported:

H3. *The chi-square goodness-of-fit test confirmed a systemic and statistically significant compliance gap across all 14 parameters ($p < 0.05$), validating that infrastructure deficits are not incidental but structuralThe one-sample t-test confirmed that stakeholder perception was significantly lower than the neutral threshold of 3.0 ($t(99) = -21.10$, $p < 0.001$), while qualitative co-occurrence analysis further validated that built environment barriers act as direct triggers for user anxiety and forced social dependency.*

4.8. Hierarchical Attribution: Root Causes of Accessibility Gaps

The accessibility gaps synthesised in the joint display (Table 9) extend beyond simple infrastructural deficits. They are rooted in a "compliance–resilience gap," which is driven by the administrative and economic structures of Indian intermediate cities. A hierarchical attribution reveals three primary causes.

1. Administrative fragmentation: Unlike unified transport authorities in metropolitan cities, intermediate cities like Udupi often face jurisdictional overlaps between city municipal councils, regional transport offices, district and zonal administrations, and private bus operators who own and operate the majority of buses. These overlaps and fragmentation lead to a lack of clear accountability for management and maintenance of the transit interface, along with first and last-mile connectivity. While municipal authorities provide the physical infrastructure, private bus operators prioritise rapid turnarounds. This operational issue results in buses stopping in active traffic lanes, rendering even compliant infrastructure nonfunctional for PwLD (as noted by P20).
2. Economic constraints—Due to limited city municipal budgets compared to metropolitan hubs, infrastructure in intermediate cities is often developed incrementally rather than holistically. This leads to partial compliance with standards or a lack of long-term management and maintenance. However, the audit reveals that even when funds are spent, a lack of technical universal design expertise leads to "engineering failures," such as the installation of slippery vitrified tiles (P19) or nonstandard steep ramps (P02). This is compounded by a lack of life cycle asset management, where maintenance is viewed as a choice of aesthetics rather than a mobility requirement, allowing garbage (P02) and broken railings (P11) to negate initial investments.
3. Informality and enforcement aspect: High reliance on private sector operators and service providers in intermediate cities makes enforcement of standards and guidelines significantly more challenging than in state-run metropolitan transport systems.

There is a clear gap between the top–down policy approach and the bottom–up resource restraints. While national mandates like the RPwD Act, accessibility standards, and guidelines set high standards, adequate funding and ground-level technical expertise required for implementation of these standards are often absent in the administrative setups of intermediate cities. Without a standardised technical audit protocol at the local level, transit interfaces are permitted for public use without verification of ramp gradient, railing continuity, use of vitrified tiles, and inadequate spatial planning, effectively creating "exclusion zones" for users of mobility aids.

Mitigating these infrastructural deficits necessitates a transition from fragmented interventions toward a coordinated multi-sectoral governance model tailored to the resource constraints of intermediate cities.

5. Discussion

These findings revealed consistent and widespread accessibility barriers across bus transit interfaces in Udupi. These barriers extend beyond design shortcomings and reflect broader structural and operational gaps. The Udupi Regional Transport Office (RTO) provided insights into the regulatory environment of the city. They suggested that the decentralised management and competition between private bus operators lead to issues like overspeeding, overcrowding, and inconsistent halting practices. These findings were validated through a mixed-methods approach and a high Krippendorff's alpha (0.822) for inter-rater reliability. Results confirmed that across all 14 evaluated parameters [24,33], the present state of bus infrastructure fell short of the established national [7,75] and international accessibility standards [35,76,87–91]. The analysis indicated that the present state of bus transport infrastructure in Udupi is challenging for all users [92]. While ref. [86]

identified high demand for technologies in Riobamba, Ecuador, our findings in Udupi suggest that built environmental interventions must precede high-tech smart features. Without physical facilities like accessible ramps and lighting, digital information systems cannot bridge the mobility gap. This observation aligns with recent predictive modelling of public transport acceptance [65] and pedestrian satisfaction [66], which emphasises that while high-tech sensitivity methods can prioritise variables, the foundational quality of the built environment remains the primary driver of transit reliability in developing nations. Our results in Udupi reinforce this trend, showing that 'justice-centred' built environment fixes must precede high-level predictive or smart city features. This study contributes to the built environmental aspects of urban transit interfaces not only in the case of similar-scale Indian cities but also to similar Asian and global contexts [39,45,46,93–97].

One of the key contributions of this study lies in examining not only whether accessibility features exist but also how they function in reality. For example, the documented ramp slope of 1:8.5 is not only a deviation from standards. For PwLD with crutches or a wheelchair, it represents dependency, physical strain, and safety risk. The causal effect of built environment features on transit flow becomes extremely critical during emergencies, necessitating clear spatial layouts for safe evacuation [98]. This illustrates how measured data need to be interpreted in relation to the capability of the end user.

The findings also indicate that accessibility challenges in intermediate cities may differ in intensity and nature from those observed in large metropolitan areas [57,99–109]. While many policies and guidelines exist, their site-level implementation remains inconsistent.

Operational gaps further compound physical barriers. The absence of disability awareness training among transport staff and the lack of maintenance suggest that accessibility concerns cannot be addressed by mere physical upgradation. Infrastructure, services, and management practices must work together cohesively.

Another important observation is user-developed adaptive strategies—such as travelling only during off-peak hours or relying on family members for support. While these coping mechanisms demonstrate resilience, they also signify infrastructural inadequacy and unequal mobility conditions.

Overall, the findings highlight the need to go beyond checklist-based compliance toward functional usability [26,110] grounded in real user experience.

The identified disparities between the design guidelines and ground-level practice suggest a need for 'inclusive management protocols' for transport infrastructure, services, and systems. Mitigating these infrastructural deficits necessitates a transition from fragmented interventions toward a coordinated multi-sectoral governance model tailored to the resource constraints of intermediate cities. To address these hierarchical issues, the study proposes:

1. Mandatory universal design audit protocol: Linking payments to contractors to a successful universal design compliance audit check;
2. Operational mandates: Integrating kerb-side boarding requirements and speed limits into private bus operating licences;
3. Dedicated interface management: To establish a multi-sectoral administrative unit to oversee the management and maintenance of transit assets as part of "critical infrastructure."

5.1. Policy Implications and Actionable Recommendations

To transition from descriptive auditing to systemic change, this study outlines three high-priority policy interventions.

1. Mandatory UD audit protocol: Linking contractor payments to a successful universal design (UD) compliance check. While the 14-parameter framework provides a holistic

diagnosis of the state of transit interface, initial enforcement should prioritise high-impact safety anchors such as vertical connectivity (P6) and lighting (P4) to achieve immediate equity gains.

2. Operational licensing reform: Integrating 'kerb-side boarding' mandates into private bus operating licenses. This specifically targets the elimination of horizontal gaps at the interface, removing the need for hazardous 'lifting' behaviours identified in user narratives.
3. Service level sensitisation: Implementing mandatory disability awareness training for transport staff. This is essential for mitigating the attitudinal barriers and social anxiety that currently deter PwLD from using the system, even where physical features may exist.

5.2. Limitations and Future Research Gaps

While this study provides a validated empirical baseline for intermediate cities, its limitations are acknowledged.

First, the use of purposive and convenience sampling may introduce selection bias. However, this strategy was a pragmatic necessity since the extreme physical barriers at transit interfaces naturally exclude many PwLD from the site, creating a 'sampling paradox' where the most affected individuals are least visible.

Second, while the overall stakeholder group (n = 100) was robust, the specific subgroup of PwLD (n = 18) is small. This reflects the 'temporal displacement' identified in the findings, where high infrastructural deficits force PwLD to avoid public transit entirely.

Third, the study focused on a single 10.2 km 'functional spine.' While this corridor is a representative microcosm of Udupi's urban typologies, future research could expand to multiple corridors across diverse intermediate cities to ensure broader generalisability. While the audit and interviews reveal significant barriers, the findings are indicative rather than causal regarding city-wide mode choice. Future research utilising longitudinal GPS tracking or city-wide travel diaries is required to quantify the exact impact of these 'compliance–resilience gaps' on aggregate ridership volumes across the broader areas.

Finally, while an equal weighting model was used for its objective baseline, future studies could incorporate global sensitivity analysis (GSA) to evaluate how alternative parameter weightings impact overall accessibility indices. By adopting these advanced modelling frameworks, as seen in recent studies on transport acceptance [65] and pedestrian satisfaction [66], future research can prioritise specific high-impact interventions for faster urban equity gains.

6. Conclusions

This study provides a detailed empirical assessment of accessibility conditions at transit interfaces in Udupi, an intermediate city in Karnataka, India. Using a convergent parallel mixed-method approach, the integrated findings successfully validated the two research hypotheses. The results supported H1, confirming through χ^2 goodness-of-fit testing that a significant and systemic gap exists between regulatory intent and built reality ($p < 0.05$). While certain features exist, they frequently do not meet the functional requirements for PwLD. This impedes independent mobility, compromises safety, and impacts the dignity of PwLD. Further, H2 was confirmed through a strong inter-rater reliability outcome (Krippendorff's alpha: 0.822) and the synthesis of stakeholder narratives via a joint display. This validated the proposed audit tool as a stable, objective benchmark for assessing diverse built environment variables in resource-constrained intermediate cities.

The synthesis reveals that accessibility at these transit interfaces is often incidental rather than intentionally integrated into planning and implementation. The study identified that the most critical "functional failure points" occur in vertical connectivity measures like ramps and information systems. Along with these aspects, noncompliance of safety and security and human resource aspects (P6, P10, P13, and P14) forces PwLD into hazardous adaptation strategies or costly private alternatives. These gaps are rooted in a fractured governance model where the lack of an integrated approach between civic administrators and dominant private bus operators prevents a cohesive, accessible transit system.

The findings suggest that inclusive urban infrastructure is built through context-responsive, user-centric, participatory, and well-detailed urban micro infrastructural interventions. The study advocates an integrated approach that prioritises built environment interventions at transit interfaces as a foundation for future smart technological integration, ensuring urban mobility and equity for all citizens. It advocates a shift from fragmented checklist-based compliance to a "justice-centred" management model. Implementing periodic, user-led accessibility audits and prioritising universal design in urban micro transit infrastructure are essential prerequisites to ensure that future smart technological integrations do not bypass vulnerable populations. This framework contributes to the broader discourse on SDG 11 by providing a methodology to enhance the inclusive design of bus transit infrastructure in Indian intermediate cities, such as Udupi, but it also helps develop inclusive, equitable, and sustainable urban bus transport systems in broader Asian and global contexts.

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Abbreviations

The following abbreviations are used in this manuscript:

PwD	Person with Disability
PwLD	Person with a Locomotor Disability
UD	Universal Design
GSA	Global Sensitivity Analysis

Appendix A

Table A1. Twenty-one bus transit nodes on the identified route with their GPS coordinates.

Sl. No.	Name of Bus Transit Node	Coordinates	Bus Transit Node Providing Access to
1	MIT transit node	13.3553, 74.7942	Educational institutions, hospital
2	Manipal Tiger Circle	13.3522, 74.7868	Educational institutions, hospital, market
3	Madhava Kripa School	13.3486, 74.7855	Educational institutions, post office, police station
4	Laxmindra Nagar	13.3482, 74.7768	Residential areas, shops
5	Indrali	13.3453, 74.7697	Railway station, residential areas
6	MGM College	13.3455, 74.7662	Educational institutions, residential areas
7	Sharada Mantapa	13.3462, 74.7621	Shops, offices, tuition classes
8	Kunjibetteu	13.3461, 74.7598	Shops, residential areas
9	Kadiyali	13.3459, 74.7582	Shops, residential areas, religious places
10	Kalasanka	13.3454, 74.7525	Shopping malls, shops, and religious places
11	Udupi City transit node	13.3436, 74.7478	Shops, offices, market, hospitals
12	Bannanje	13.3458, 74.7375	Inter-city bus terminus, commercial spaces
13	Karavali Junction	13.3465, 74.7354	Shops, transit hub, hotels
14	Adi Udupi	13.3476, 74.7325	Residential areas, shops
15	Income Tax Office	13.3482, 74.7295	Offices, residential areas
16	Pandubettu	13.3473, 74.7226	Residential areas, shops, and commercial spaces
17	Kalmady	13.3477, 74.7173	Residential areas, shops
18	Koragajja	13.3483, 74.7138	Residential areas, religious places
19	Kalmady Bridge	13.3488, 74.7103	Residential areas
20	Yeluru	13.3485, 74.7063	Residential, commercial areas
21	Malpe transit node	13.3485, 74.7032	Port, beach, commercial areas

Appendix B

Format of inter-rater reliability audit

Bus transit interface accessibility assessment for persons with locomotor disabilities (5-point Likert's scale)

Assessment Details:

Assessment Location: _____

Date of Assessment: _____

Time of Assessment: _____

Rater Name (Optional)/ID: _____

Instructions for Raters:

This form is used to assess the accessibility of bus transit interfaces for persons with locomotor disabilities. You are requested to evaluate each item using a 5-point Likert's scale based on the following 14 built environment parameters. Kindly assign a rating based on the scale provided and add any relevant comments or observations that support your rating. Be as objective as possible and consider the perspective of a person with a locomotor disability navigating this environment. Please rate each checklist item independently.

Rating Scale:

To ensure the 14 parameters are fully recoverable for future replication, each parameter is graded against binary technical thresholds derived from National Building Code (NBC)—2016 standards (e.g., ramp slope $\leq$ 1:12; lighting $\geq$ 15 lux). Non-compliance (score 1) to be recorded for features that are absent, broken or exceed safety threshold, while compliance (score 5) to be given for aspects meeting these benchmarks. No arbitrary weighting to be applied to maintain a neutral empirical baseline. The following rating system is to be followed.

1. Not accessible: The feature is either not present at all or, if present, is unusable for persons with locomotor disabilities. Does not meet any accessibility requirements.

2. Minimally accessible: The feature is present and usable but has several barriers or limitations for persons with locomotor disabilities. Meets only basic or partial standards.
3. Moderately accessible: The feature is present but needs improvement. It complies with standards, but with limitations.
4. Mostly accessible—The feature is functional but needs further improvement. It is compliant with minor limitations.
5. Accessible: The feature fully meets the needs of persons with locomotor disabilities or exceeds standards.

(Note—Your ratings will be used only for statistical reliability analysis)
Assessment Parameters:

Table A2. Assessment parameters for conducting IRR.

Sl. No.	Built Environment Variables	Rating-(1–5). (NA/Not Accessible/ Minimally Accessible/Moderately Accessible/Accessible)	Comments/Observations
1	Reaching transit interface, connectivity, and parking		
2	Space allowances, levels		
3	Surface materials and finishes		
4	Lighting		
5	Seating/waiting		
6	Ramp slope		
7	Sidewalks and kerbs		
8	Railings		
9	Circulation/movement		
10	Safety and security		
11	Maintenance & management		
12	Water and sanitation facilities		
13	Human resources		
14	Signages and communication		

Additional Notes for Raters:

- Please consider both the physical aspects of the environment and how a person with a locomotor disability would interact with them.
- Think about potential obstacles, ease of movement, availability of necessary facilities, and clarity of information.
- If possible, try to simulate using a mobility aid (e.g., observing from a seated position, using a cane) to gain a better understanding of the accessibility challenges.

Any further suggestions/comments.
Thank you for your support and suggestions.

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