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Improving Sustainable Urban Mobility Through Bus Service Optimization: A Case Study of Vadodara

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Abstract

This paper investigates how bus service optimization to improve sustainable urban mobility in Vadodara, a medium-sized Indian city, which is experiencing rapid motorization. The study combines primary survey data (n = 336) and secondary household-level data (approx. 7,000 records), which is analyzed using spatial and network performance analyses to assess accessibility, operational efficiency and service quality of the current bus network. The results show that peripheral service coverage and significant deficiencies in service reliability and availability, as are the accessibility to first- and last-mile accessibility and the integration with Intermediate Public Transport (IPT). While IPT is an affordable last-mile travel choice for most of its users, it increases overall travel costs. This cost burden is especially high for low-income travelers. Inadequate pedestrian infrastructure and the gender-related differences in perceived accessibility also reduce the attractiveness of public transport. Based on these findings, the study recommends based on the findings: Network restructuring, optimizing the frequency of services, improving pedestrian infrastructure, formal integration of IPT into the public transport system as a first- and last-mile feeder service. The findings show that accessibility, service quality, safety and multimodal integration can greatly increase bus ridership and enable sustainable urban mobility in medium-sized cities.

Keywords- bus service optimization, intermediate public transport, last-mile connectivity, sustainable urban mobility, transport planning, Vadodara

1. Introduction

Urban mobility is a key determinant of sustainable urban development, particularly in rapidly urbanizing developing countries. Growing motorization, driven by rising incomes and changing travel preferences, has increased congestion, environmental degradation, and inefficiencies in urban transport systems. This trend is particularly evident in India where there has been a significant increase in the number of privately owned vehicles, especially two-wheelers that have contributed to the decline in the use of public transport.

Public transport, particularly bus services, plays a central role in addressing these challenges. The efficiency of bus systems, however, depends on several factors, including network coverage, service frequency, reliability, and accessibility. Bus systems in most Indian cities are limited in scope of space coverage, level of service, and integration with other modes, making them less competitive than private modes of transport.

First- and last-mile connectivity remains one of the most significant challenges facing urban public transport systems. IPT services, such as auto-rickshaws and shared mobility, often fill this gap but do so in a very unregulated and poorly integrated way. This leads to higher travel costs, fragmented travel patterns, and reduced system efficiency.

These challenges are also evident in Vadodara, a rapidly developing medium-sized city. Although the city has a well-developed bus network, the network is characterized by an imbalanced distribution of services, low accessibility in the peripheral zones, and low multimodality of the system. The inadequate alignment of land use patterns and transport supply also contributes to mobility inefficiencies and greater reliance on a private mode.

It is against this backdrop that the study seeks to assess the effectiveness of the current bus system in Vadodara and what can be done to enhance sustainable urban mobility. The study combines spatial analysis, travel behaviour and network performance analyses to analyze accessibility gaps, service inefficiencies, and the role of IPT in last-mile connectivity. The findings provide evidence-based recommendations to improve accessibility, effectiveness of operations, and multimodal integration in the medium-sized cities.

2. Literature Review

The mobility of urban areas has been a subject of extensive research with regard to land use, travel demand, infrastructure, and policy frameworks, especially with the increasing congestion, environmental issues, and social inequities. The change towards sustainable urban mobility has prompted a growing focus on accessibility-oriented planning, as opposed to mobility-oriented approaches. Banister (2008) stressed the necessity to decrease the travel demand, promote the modal shift, and compact urban development, whereas Zhou (2012) focused on the equilibrium between environment, economy, and social aspects of transport systems. These views make public transport, especially buses, an essential element in decreasing the car dependency and increasing accessibility.

The interaction between transport and land use has also been greatly researched. Through the 3Ds model of density, diversity and design, Cervero and Kockelman (1997) demonstrated that urban form substantially plays a role in travel behaviour. In a similar vein, as demonstrated by Ibraeva et al. (2020), transit-oriented development (TOD) promotes access and decreases the reliance on a private vehicle when it is supported by efficient transit. These studies show that the efficiency of transport is strongly associated with spatial planning and urban structure.

Public transport systems that use buses continue to be at the heart of urban transport, particularly in the developing world. As pointed out by Vuchic (2005) and Ceder (2016), the design of networks, reliability of services, scheduling and operational efficiency are the determinants of system performance. Ibarra-Rojas et al. (2015) also found that inefficiencies occurred due to the lack of coordination between routes, frequencies, and demand.

The design and optimization of transit networks have developed and there have been early models, including the genetic algorithm-based model by Fan and Machemehl (2006) which showed an improvement in the efficiency of the network under varying demand conditions. More recent literature has embraced integrated frameworks; Kibria et al. (2025) proposed simultaneous optimization of stops and routes to enhance accessibility, whilst Jiang et al.

(2025) focused on micro-circulation and feeder-based planning in TOD contexts to enhance last-mile connectivity. These changes suggest a move towards data-oriented and access-centric optimization mechanisms.

The concept of accessibility and equity have become the critical dimensions of transport planning. Karner (2018) emphasized the inequities in providing transit services based on route-based accessibility metrics, and Jiao (2017) introduced the term of transit deserts to identify the under-served areas. Singh and Sharma (2020) also showed how GIS-based accessibility analysis can be used to assess bus systems and plan their interventions.

The research on travel behaviour offers more information on the mode choice dynamics. Jain and Tiwari (2019) noted that the lack of a proper transport infrastructure in developing cities usually leads to the increasing use of the private and informal ones. The cost, reliability, accessibility, and convenience are examples of factors that influence mode choice, which explains the need to improve the quality of the services provided in the industry to turn the situation around.

Urban transport issues in India are not new issues. A change towards people instead of vehicle movement is advocated by the National Urban Transport Policy (Ministry of Housing and Urban Affairs, 2014), and the URDPFI Guidelines (Ministry of Housing and Urban Affairs, 2017) focus on integrated land use and transport planning. Among the critical problems outlined by the Institute of Urban Transport (2015) is the insufficient fleet size, the lack of quality service, and the decreasing ridership. Mohan and Tiwari (2019) also emphasized the growing motorization and the absence of integrated planning as significant issues. The urgency of the need to improve public transport systems to deal with congestion and environmental effects is supported by data provided by the Ministry of Road Transport and Highways (2020), as well as international reports (UN-Habitat 2022; United Nations 2018; World Bank 2019).

The city level planning documents of Vadodara have significant contextual information. The Comprehensive Mobility Plan (CEPT University 2019) revealed the lack of coverage, poor integration, and the increasing dependency on cars and motorcycles to be the main issues, whereas the Vadodara Municipal Corporation (2023) focused on the lack of efficiency and infrastructure in the transport systems. These results suggest that medium-sized cities encounter the same issues as large metropolitan areas but have a low probability of having the resources to develop advanced transportation solutions, so bus system optimization is especially applicable in this case.

Although a considerable amount of research has already been done on sustainable urban mobility, there are a number of gaps that have yet to be addressed. First, most of the existing literature has been conducted on large metro cities or theoretical optimization studies, while there are fewer empirical studies in medium-sized Indian cities with varying financial, operational and infrastructural constraints. Second, the previous research usually focuses separately on network optimization, accessibility assessment, travel behaviour and Intermediate Public Transport (IPT); and few studies combine these dimensions in a comprehensive analytical approach to assessing bus system performance. Third, GIS accessibility measurement and operational performance assessment has been routinely used, but few studies integrate spatial information with user perception and household journeys data to uncover physical and behavioural constraints for public transport use. Last but not least, the function of IPT as a first- and last-mile service that is structured remains under-researched in integrated public transport planning. In order to fill these gaps, a holistic approach is taken in the present study, which includes a spatial accessibility analysis, assessment of travel behaviour, evaluation of operational network performance and integration of IPTs, based on primary survey data and large-scale household travel data for the city of Vadodara. The findings offer evidence-based solutions that can enhance the efficiency of bus service in medium-sized cities and help ensure sustainable mobility in cities.

3. Data and Methodology

This study follows an integrated methodological approach in the evaluation and optimization of the bus transit system in Vadodara. The proposed framework integrates spatial analysis, quantitative assessment, and behavioural analysis to investigate the interrelationship existing between transport supply, travel demand and urban structure. The framework attributes key determinants of the system performance to accessibility, operational efficiency, and user behaviour, with specific focus on how IPT can contribute to first- and last-mile connectivity.

3.1 Study Area and Research Design

The present study is conducted in the main study area of Vadodara Municipal Corporation (VMC), Gujarat, India. The VMC is the core urbanised area of the Vadodara city covering the area of about 220.33 sq.km. The city is also a significant industrial, commercial and educational hub in the central Gujarat region and has seen the growth of the city in recent decades and the demand for travel to it is growing.

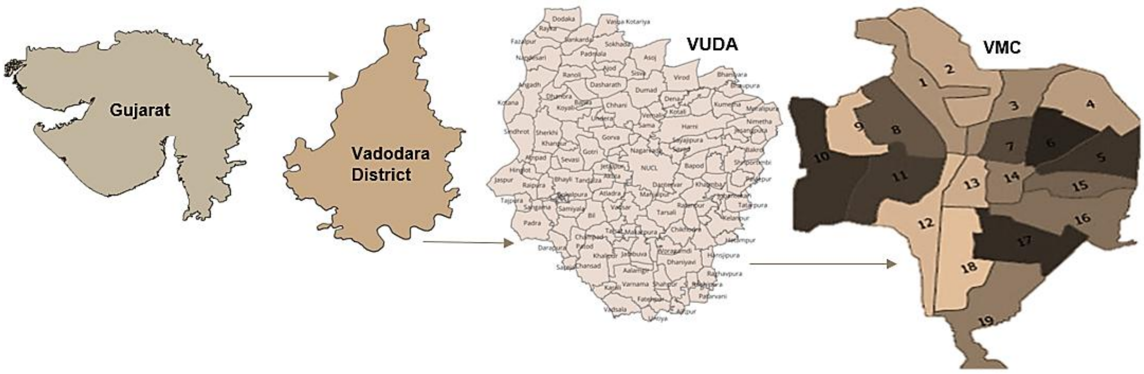

Figure 1: VMC Boundary and Regional Planning Context of Vadodara

Note: The boundary of VUDA is shown for regional planning context and detailed spatial and transport analysis is limited to the VMC area.

The main focus of the study is on the urban transport features, bus network performance, accessibility conditions and travel behavior in the VMC area. The Vadodara Urban Development Authority (VUDA) boundary is mentioned in some GIS maps and regional planning scenarios, but detailed analysis and assessment of this study are restricted to the VMC boundary.

The city sees a high concentration of urban development in the core areas and spreading out residential and industrial areas in the periphery. Relatively good transport accessibility is found in central areas, which also have a higher concentration of passenger demand. On the contrary, peripheral areas are characterized by service gaps, lower first- and last-mile connectivity, and more reliance on private and IPT modes. The current bus network comprises approximately 50–60 routes and 300-350 buses, with different efficiencies and spatial coverage.

The study takes a mixed-methodology, incorporating spatial, behavioural and network performance analysis. The methodology consists of data collection, spatial assessment using GIS to detect system inefficiencies and identify potential optimization strategies.

3.2 Data Sources and Sampling

Both primary and secondary data are used in the study to make sure that the study is comprehensive. The structured questionnaire was given to 336 respondents in various spatial zones of the city to collect primary data. The survey captured socio-demographic, travel behaviour, mode choice, bus usage pattern, accessibility conditions, service perceptions, IPT usage, and influencing factors of modal shift.

Seven thousand (7,000) household level survey records were collected from the secondary household survey dataset by Pankaj Prajapati (2025), and other data such as bus route, bus stop locations, boarding and alighting of passengers, distribution of land use and ward level demographic and travel characteristics were collected. This study used the secondary data for GIS-based spatial and operational analysis. Also, GIS shape files of VMC and surrounding regional administrative boundaries were used for spatial analysis for contextual mapping.

The stratified sampling method was used to guarantee the presence of central, intermediate and peripheral areas. The extensive secondary data allows very strong spatial and demand analysis, whereas the primary survey provides behavioural insights, which will ensure a high level of breadth and depth in analysis.

3.3 Analytical Framework

The analytical framework is a combination of spatial, operational, and behavioural dimensions. The GIS-based analysis was used to determine service coverage, accessibility and spatial distribution of demand. Bus stop catchment areas were defined based on a 500 m walking threshold to determine service gaps and underserved areas. These spatial products were superimposed on patterns of land use and distribution of demand to test discrepancies between service delivery and travel demand.

Existing bus route network and the stop distribution within VMC were spatially represented to evaluate the coverage of the existing bus network and to identify the access gaps.

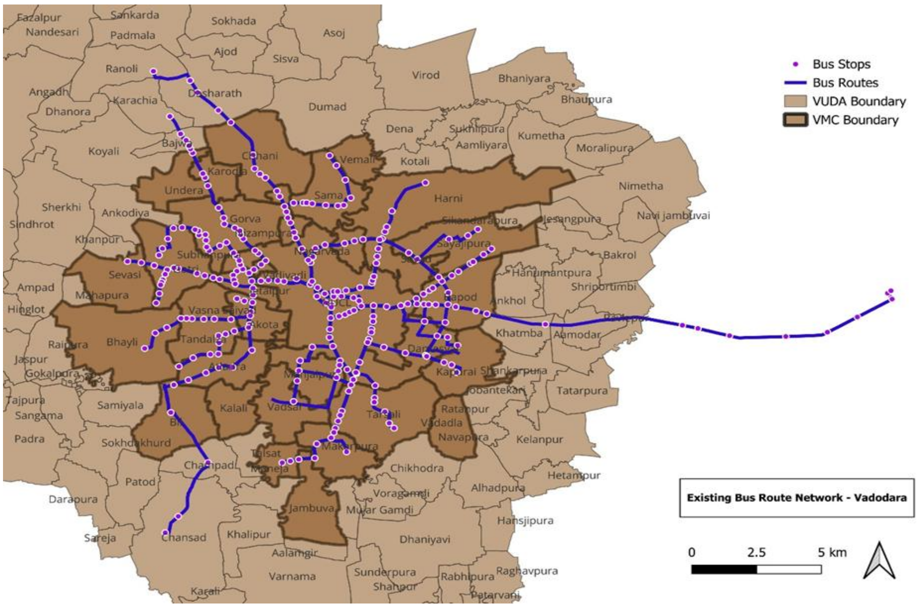

Figure 2: Current distribution of bus stops and bus route network within VM

The data on passenger boarding and alighting was used to evaluate the operational performance on a route and stop basis, and assess the efficiency of the route, distribution of passengers, and directional imbalances. Primary survey data were used to conduct behavioural analysis to comprehend mode choice patterns, the constraints of accessibility, and how the users perceive the quality of the services.

The combination of datasets enables validation of spatial results with behavioural observations. As an example, the areas that were defined as service gaps by using GIS analysis were analysed in relation to user reliance on IPT and perceived constraints on accessibility. In the same way, hotspots of demand were examined together with how the users perceived the services in terms of quality and reliability to detect structural inefficiencies.

3.4 Scope and Limitations

The research problem is to examine the accessibility, service coverage, demand distribution and the user behaviour of bus transport system of Vadodara. Although the methodology presents a complete analytical framework, the study has several limitations. Real-time operational data, such as GPS tracking, and detailed financial or cost-benefit analysis of suggested strategies are not part of the analysis. Also, the aspects of dynamic scheduling and operational control are not studied in detail.

The social safety consideration is measured using perception-based measures such as walking conditions, gender-based patterns of accessibility, and user perceived restrictions. Though they offer quantifiable indicators of safety-related factors that affect the use of public transport, they do not provide a specific safety assessment framework, which may be explored in future studies.

Nevertheless, despite these drawbacks, the methodology provides a solid basis to identify structural inefficiencies and develop evidence-based planning interventions.

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4. Results and Discussion

This section combines primary (n = 336) and secondary (~7,000 households) data to analyse the behaviour of travel, restrictions in accessibility, and the performance of operations of the bus network in Vadodara. The analysis shows the structural inefficiencies that affect the use of public transport and gives the empirical support to the optimization strategies.

4.1 Travel behaviour and socio-economic characteristics

The socio-economic profile indicates that the majority of respondents belong to the economically active age group (18–40 years), and a high concentration of students and employees working in the service sector. The ownership of vehicles, particularly two-wheelers, is income dependent which supports the reliance on the personal modes.

Table 1: Consolidated Socio-Economic Characteristics and Mobility Attributes

Dimension	Key Pattern	Analytical Insight
Gender × Age	Majority within 18–40 age group	Signifies economic activity majority.
Gender × Occupation	Females: students (54%); Males: service sector (43.5%)	Adaptive of occupational gender division.
Gender × Income	Increased female share in high incomes.	Proposes a wide range of socio-economic representation.
Age × Occupation	18–25 dominated by students (58%); 26–40 by service class (61.3%)	Obvious employment transition towards life-cycle.
Age × Income	Concentration of income in 4160 age group (63.6% above 1 lakh) higher.	The salary is growing with age and experience.
Occupation × Vehicle Ownership	Working groups had high ownership of two-wheelers and mixed vehicles.	Denotes reliance on privates.
Income × Vehicle Ownership	Multi-vehicle ownership is exhibited in higher income groups.	Close relationship between income and motorization.

The findings highlight:

- High mobility on a daily basis that is motivated by work and education.
- Peak-oriented travel patterns
- Evident association between income and motorization.

Patterns of travel behaviours attest to the fact that the demand in mobility is predominantly routine.

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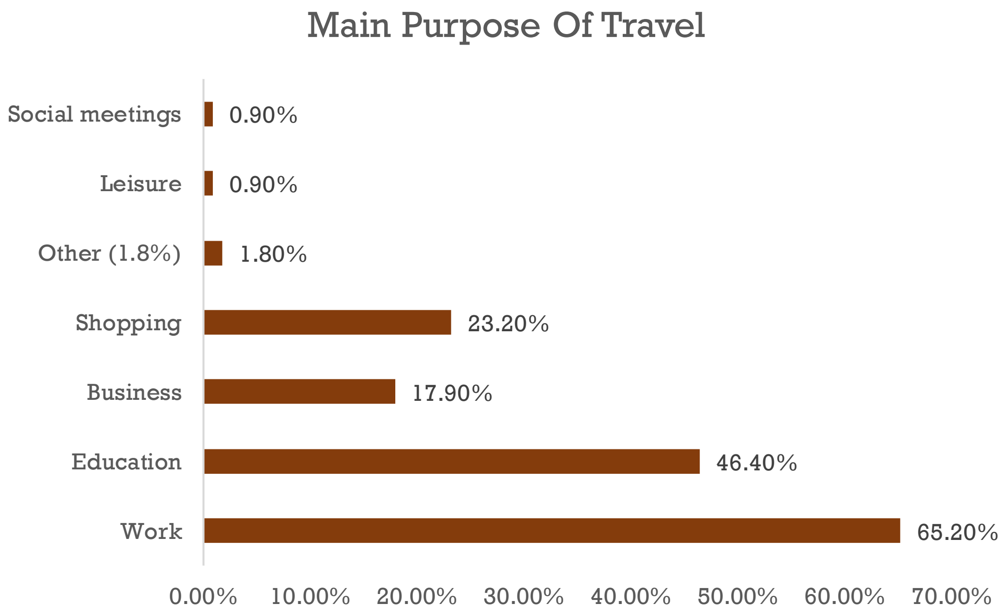

Figure 3: Main Purpose of Travel

The work-related (65.2%) and education-related trips (46.4%), confirm a peak-oriented demand structure. The forms of secondary trips like shopping and business are relatively small.

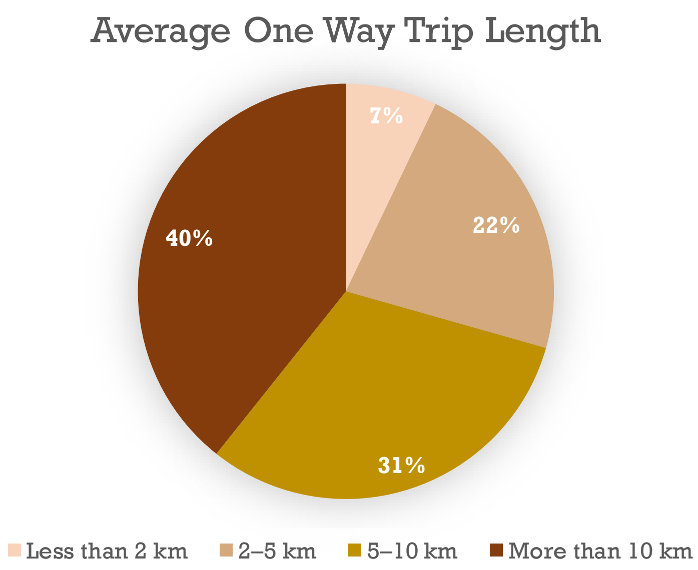

Figure 4: Average One-Way Trip Length Distribution

The average trip lengths are mostly medium and long distance, with more than 70% of them exceeding 5 km. This is in line with the operational advantages of bus based systems. The fact that people are still using their own vehicles in spite of favourable trip characteristics, however, suggests inefficiencies in service provision and not a lack of demand.

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The overall results imply that there is a high latent potential to bus ridership which is limited mainly by issues of accessibility, quality of service, and integration challenges rather than because of lack of demand.

4.2 Bus Usage, Accessibility, and Service Perception

Bus usage remains low across all socio-economic groups, with the majority of the respondents indicating occasional or no bus use.

Table 2: Determinants of Bus Usage Frequency (Consolidated Analysis)

Factor	Key Pattern	Analytical Interpretation
Gender	High non-usage among females (68%) and males (54.8%)	Indicates system-wide low adoption
Age Group	26–40 group shows highest non-usage (74.2%)	Working population prefers private modes
Occupation	Business (82.4%) and retired (75%) show highest non-usage	Bus system not aligned with flexible trip needs
Income	Higher income groups show lower usage (78.1% non-users)	Strong income–mode shift relationship
Vehicle Ownership	Multi-vehicle owners show high non-usage (64.4%)	Private mobility substitutes bus usage
Distance to Stop	Non-usage increases beyond 500 m (64.2%)	Accessibility is a key barrier
Trip Length	Bus usage increases with trip length (>10 km: 50% occasional)	Buses are more viable for longer trips
Travel Purpose	Business & shopping trips show negligible usage	Bus system not suited for non-routine trips
Fare Affordability	Even "affordable" users show low daily usage	Cost is not the primary barrier

The analysis shows that a greater number of vehicles owned privately and higher levels of income significantly reduce bus usage, whereas accessibility (distances to bus stops in particular) is shown to be a critical factor. Fare affordability is not a significant limitation, and therefore, an increase in service quality and convenience is more effective in increasing ridership.

Analysis of accessibility indicates significant barriers to accessibility (first- and last-mile connectivity).

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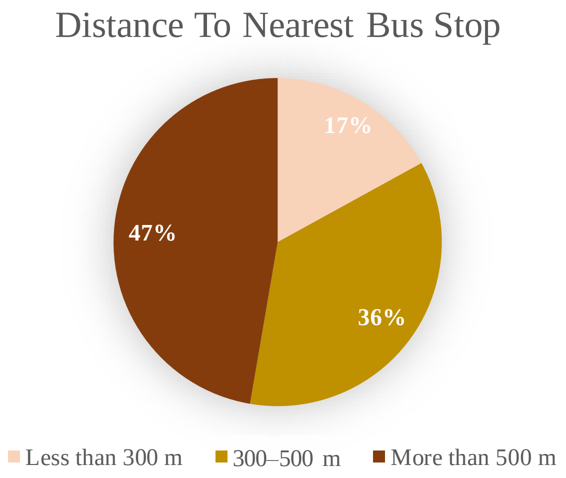

Figure 5: Distance to Nearest Bus Stop

Nearly half (47%) of the respondents walked over 500 m to the bus stop, a distance that exceeds the recommended level.

The GIS based catchment analysis also shows that there are large areas in the periphery that are not within the recommended walk distance.

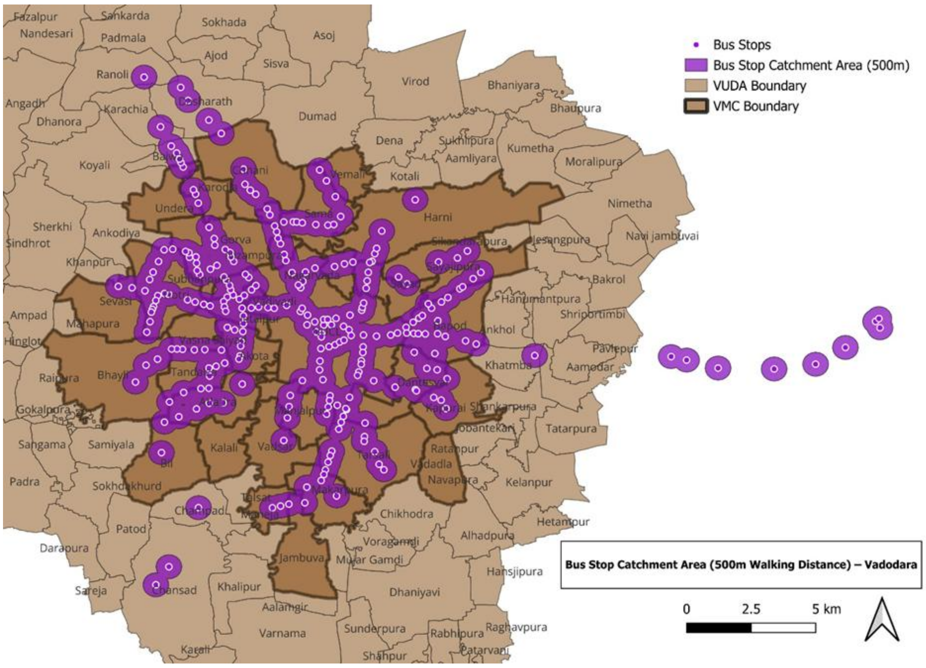

Figure 6: Bus Stop Catchment Area (500m Walking Distance) within VMC

The identified service gap areas that are beyond the effective catchment zones were also identified.

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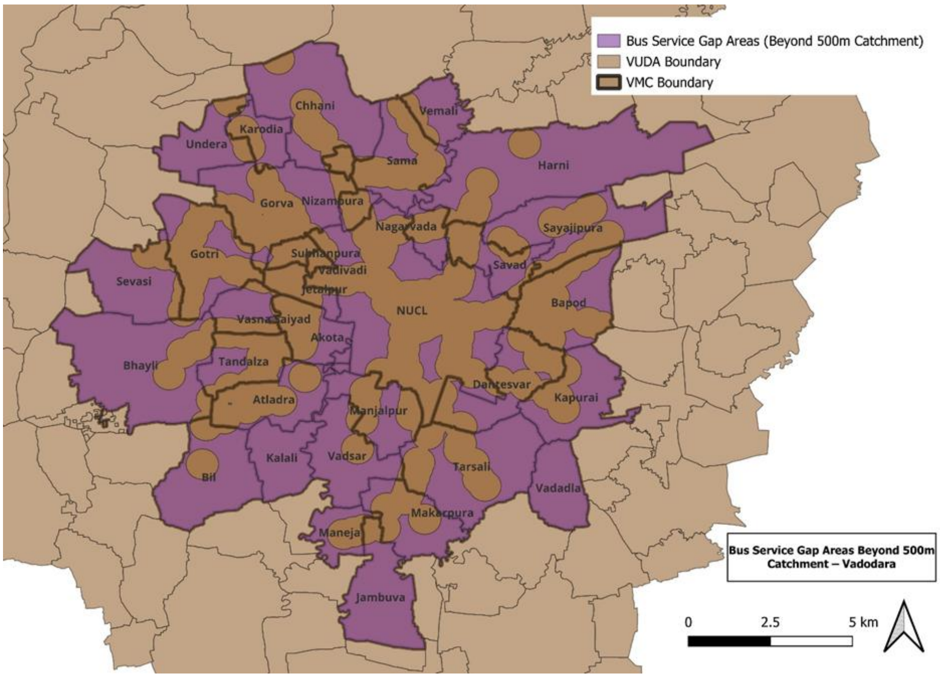

Figure 7: Bus Service Gap Areas Beyond 500m Catchment within VMC

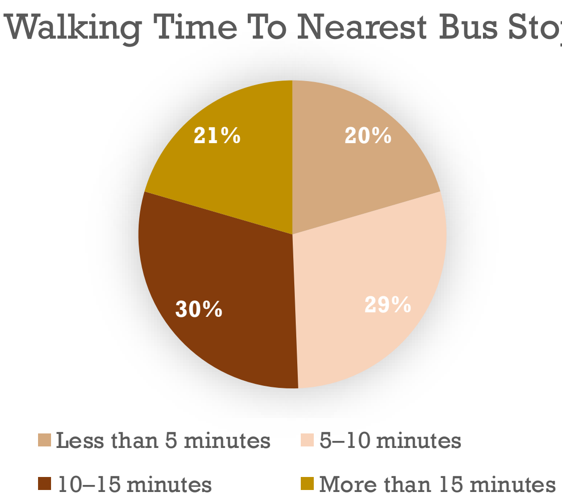

Figure 8: Walking Time to Nearest Bus Stop

Nearly a third of users take over 10-15 minutes to walk, which is not very well distributed spatially, with stops not being well dispersed, and the pedestrian infrastructure being inadequate. These circumstances decrease the useful service catchment and augment reliance on IPT and private modes.

The concept of social safety becomes a significant behavioural determinant and is related to the service quality and accessibility.

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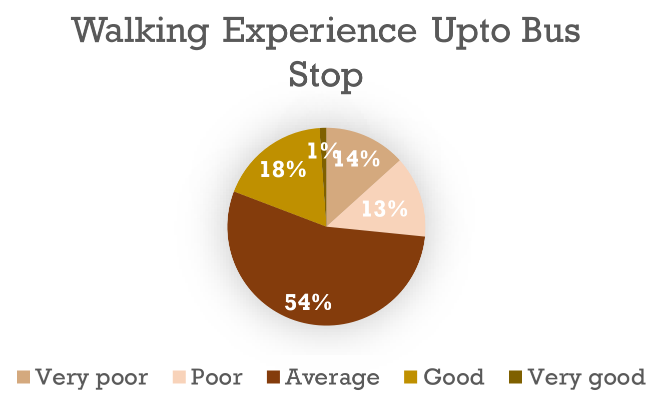

Figure 9: Walking Experience to Bus Stops

Most of the participants have average to poor walking conditions, which is manifested in the inadequate pedestrian infrastructure, and unsafe access environment. The difference among genders also suggests a greater perceived vulnerability of female users.

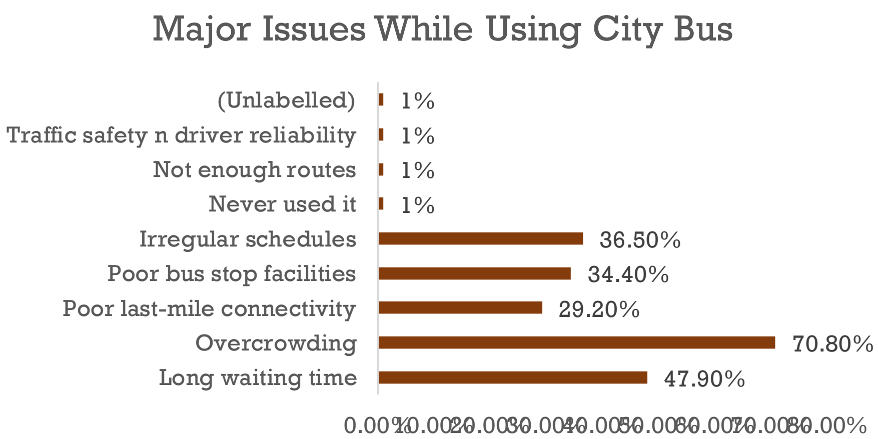

Figure 10: Major Issues Reported by Bus Users

Overcrowding and too long waiting times are cited as key issues that are likely to impact comfort, reliability, and perceived safety.

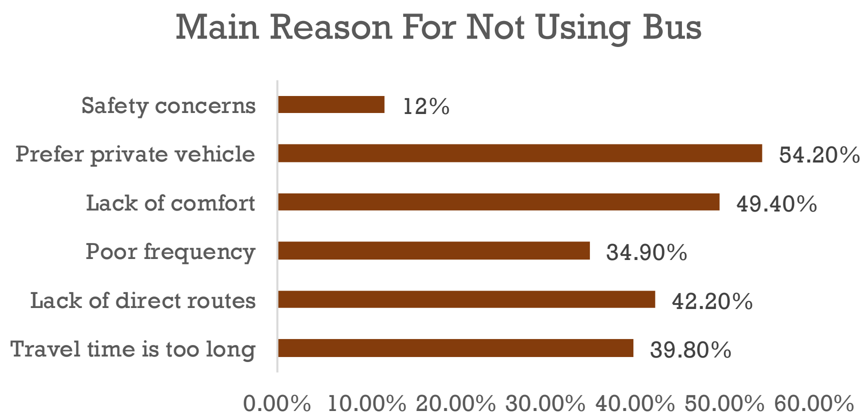

Figure 11: Reasons for Not Using Bus Services

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Although not the overwhelming factor, safety concerns lead to lower adoption in combination with inefficiencies in the services and discomfort. In the findings, the safety has been defined as a quantifiable and determining aspect of the use of public transport.
The application of last-mile connectivity (LMC) is definitive when it comes to determining bus adoption.

Table 3: Last-Mile Connectivity and Modal Shift Behaviour (Consolidated Analysis)

Dimension	Key Observation	Analytical Insight
Gender	Females (55.2%) rate LMC as very important	Higher sensitivity to accessibility issues
Age Group	26–40 group shows highest LMC importance (61.9%)	Working population values efficiency
Distance to Stop	LMC importance declines slightly beyond 500 m	Accessibility influences perception
Mode Users	Bus users' rate LMC as highly important (100%)	Reinforces dependency on connectivity
Likelihood to Shift	Majority fall under "maybe" category (40–57%)	Indicates latent demand
Income Groups	Lower-income groups show higher willingness to shift	Cost-sensitive groups prefer buses
Vehicle Ownership	Non-owners and bicycle users show highest shift potential	Captive users more responsive
Bus Frequency	Frequent users show higher likelihood to shift	Service reliability influences behaviour
LMC Importance vs Shift	High LMC importance → higher shift probability	Direct causal relationship

Findings show:

- Good relationship between LMC and readiness to change.
- The latent demand was high (very high maybe) category.
- High potential of shifting among low-income and non-vehicle users.

Bus fares are low, but the price of IPT + bus increases the burden of travel, in particular, to lower-income groups, which explains the necessity of bus fares integration.

4.3 Bus Network Performance Analysis

The analysis of secondary data indicates that significant operational inefficiencies were identified across the bus network of the bus network.

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Table 4: Route Performance Summary of Vadodara City Bus Network

VADODARA CITY BUS — COMPREHENSIVE ROUTE PERFORMANCE ANALYSIS

Rank	Route	Length (1-Way km)	Total KM (Both Dir.)	Outbound Boarding	Outbound Alighting	Inbound Boarding	Inbound Alighting	Total Passengers	Pass. Density (Pass/km)	Imbalance Ratio (O/I)	Stops Outbound	Stops Inbound	Total Stops	Avg Board per Stop	Efficiency Grade	Imbalance Category
1	3C	25.885	51.770	107	107	88	89	195	3.77	1.22	32	32	64	3.05	A+ (Excellent)	Balanced
2	19A	13.467	26.934	94	94	56	56	150	5.57	1.68	23	23	46	3.26	A+ (Excellent)	High Outbound
3	9A	10.069	20.138	48	48	77	77	125	6.21	0.62	23	23	46	2.72	A (Very Good)	Moderate Inbound
4	17A	11.222	22.444	62	62	55	55	117	5.21	1.13	29	29	58	2.02	A (Very Good)	Balanced
5	4A	9.925	19.850	71	71	45	45	116	5.84	1.58	16	16	32	3.62	A (Very Good)	High Outbound
6	9D	13.464	26.928	47	47	68	68	115	4.27	0.69	22	22	44	2.61	A (Very Good)	Moderate Inbound
7	26B	8.088	16.176	40	40	75	75	115	7.11	0.53	21	21	42	2.74	A (Very Good)	Moderate Inbound
8	12	11.599	23.198	54	54	59	59	113	4.87	0.92	25	25	50	2.26	A (Very Good)	Balanced
9	9B	9.967	19.934	71	71	39	39	110	5.52	1.82	22	22	44	2.50	A (Very Good)	High Outbound
10	22	17.378	34.756	66	66	44	44	110	3.17	1.50	20	20	40	2.75	A (Very Good)	Moderate Outbound
11	8	9.279	18.558	41	41	57	57	98	5.28	0.72	21	21	42	2.33	B (Good)	Moderate Inbound
12	18	9.501	19.002	39	39	59	59	98	5.16	0.66	23	23	46	2.13	B (Good)	Moderate Inbound
13	27	7.972	15.944	76	74	21	21	97	6.08	3.62	24	24	48	2.02	B (Good)	Severe Outbound
14	15	8.919	17.838	50	50	44	44	94	5.27	1.14	18	18	36	2.61	B (Good)	Balanced
15	30	9.091	18.182	43	43	47	47	90	4.95	0.92	26	26	52	1.73	B (Good)	Balanced
16	4	9.836	19.672	68	68	18	18	86	4.37	3.78	24	24	48	1.79	C (Average)	Severe Outbound
17	31	11.256	22.512	53	53	30	30	83	3.69	1.77	29	29	58	1.43	C (Average)	High Outbound
18	13A	12.883	25.766	54	54	27	27	81	3.14	2.00	33	33	66	1.23	C (Average)	High Outbound
19	23	8.507	17.014	53	53	19	19	72	4.23	2.79	20	20	40	1.80	C (Average)	Severe Outbound
20	10	11.588	23.176	49	49	17	17	66	2.85	2.88	16	15	31	2.13	D (Below Avg)	Severe Outbound
21	27A	7.418	14.836	45	45	20	20	65	4.38	2.25	18	18	36	1.81	D (Below Avg)	High Outbound
22	11	9.435	18.870	39	39	23	23	62	3.29	1.70	18	18	36	1.72	D (Below Avg)	High Outbound
23	10D	9.811	19.622	16	16	45	45	61	3.11	0.36	21	21	42	1.45	D (Below Avg)	High Inbound
24	7	9.617	19.234	38	38	15	15	53	2.76	2.53	22	22	44	1.20	D (Below Avg)	Severe Outbound
25	23D	3.683	7.366	8	8	18	18	26	3.53	0.44	11	11	22	1.18	E (Poor)	High Inbound
TOTAL	25 Routes			269.86		1332	1330	1066	1067	2398	4.54	1.57	557	556		

The distribution of passengers is very unequal, since there are few routes with high levels of efficiency and most routes are at moderate to low levels of performance. The demonstration of high-demand corridors is more highly utilized, and peripheral routes are less utilized.

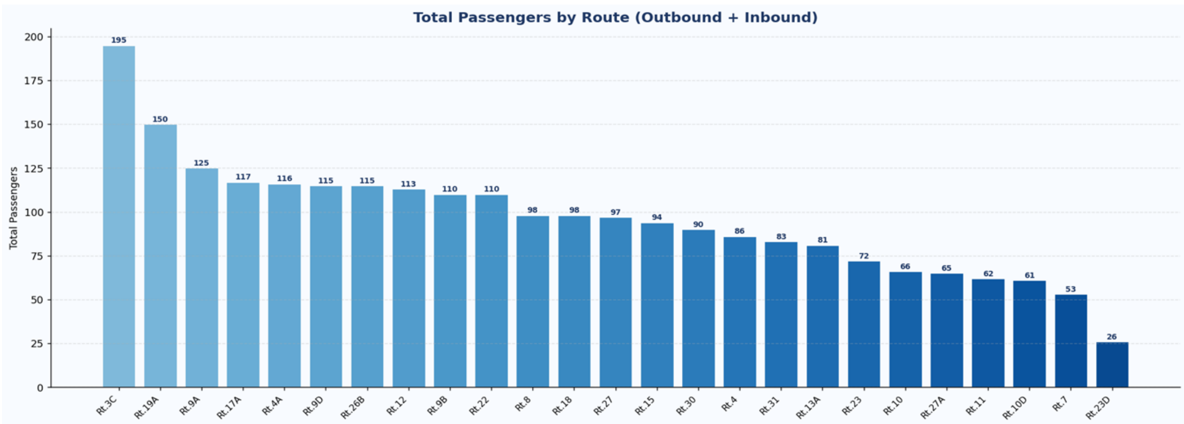

Figure 12: Total Passengers by Route (Outbound + Inbound)

Passenger flows are concentrated in a limited number of routes which implies that demand concentrates on a small number of routes and the performance of the network is uneven.

Spatial hotspot analysis shows that the demand for passengers is concentrated around the nodes of major commercial and institutional activities, as well as transport activities.

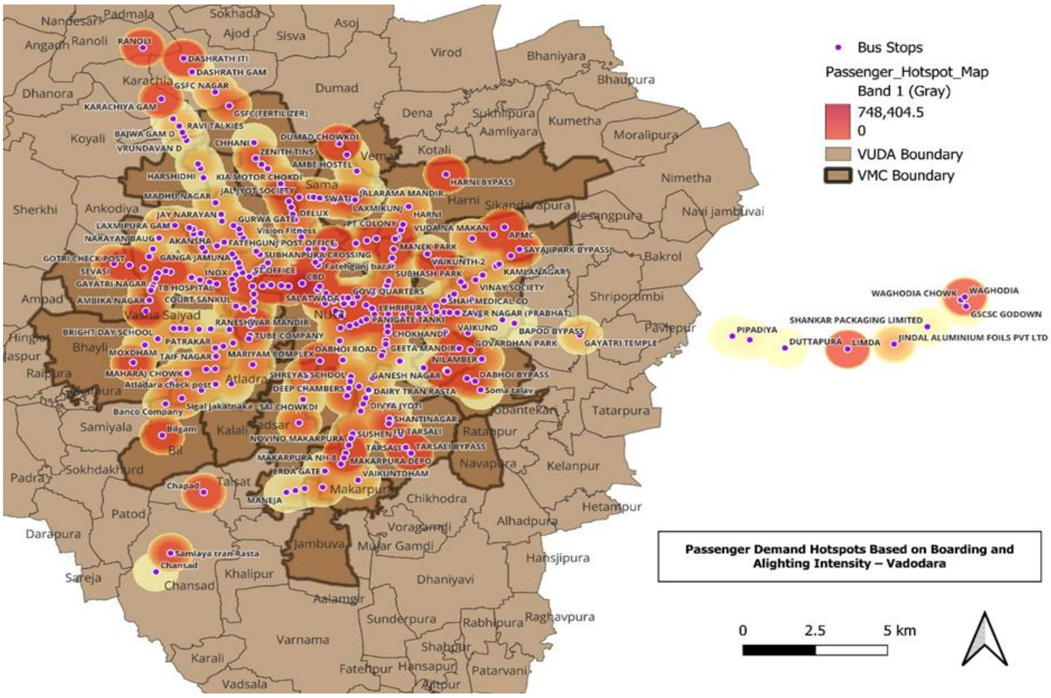

Figure 13: Passenger Demand Hotspots Based on Boarding and Alighting Intensity – Vadodara

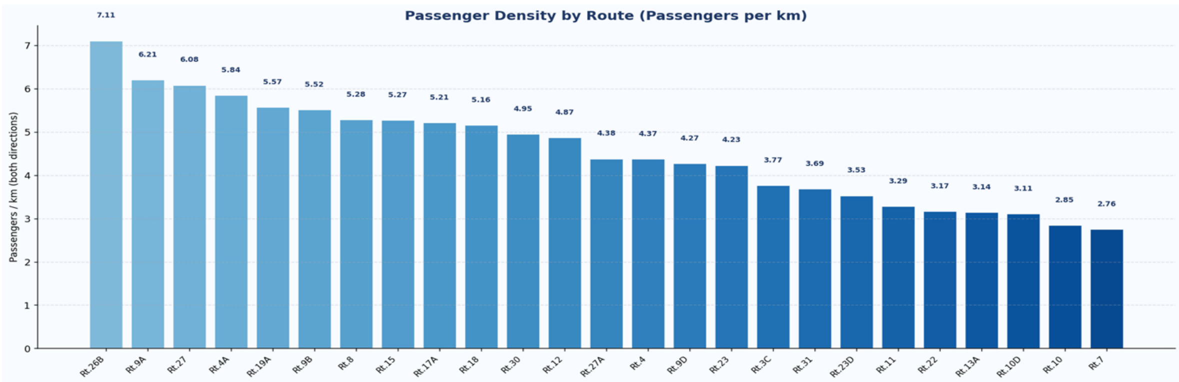

Figure 14: Passenger Density by Route (Passengers per km)

The shorter and the medium routes are more likely to display efficiency, whereas longer routes are characterised by low passenger density, indicating route design and demand mismatches.

Stop-level analysis also indicates the existence of inefficiencies in the allocation of demand.

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Figure 15: Route 3C – Stop-wise Boarding and Alighting Pattern

As seen in analysis of Route 3C, few stops make up the majority of total ridership, especially in major activity centers like CBD areas. Some of the intermediate stops have low activity which means that there is uneven distribution of passengers along the route.

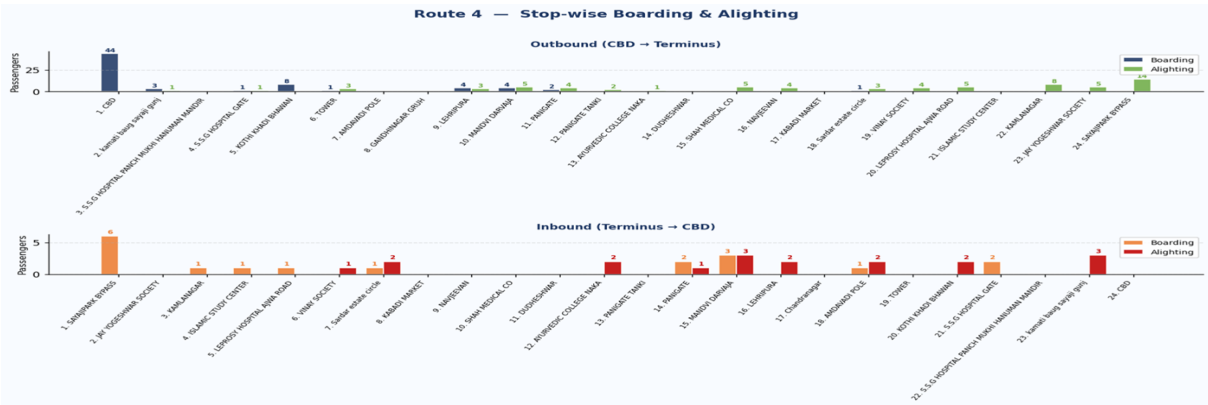

Figure 16: Route 4 – Stop-wise Boarding and Alighting Pattern

The same trend is seen in the Route 4 wherein demand is concentrated at major nodes, whilst several stops have a zero boarding and alighting. This implies that there are inefficiencies in the spacing of stops and that there can be rationalization.

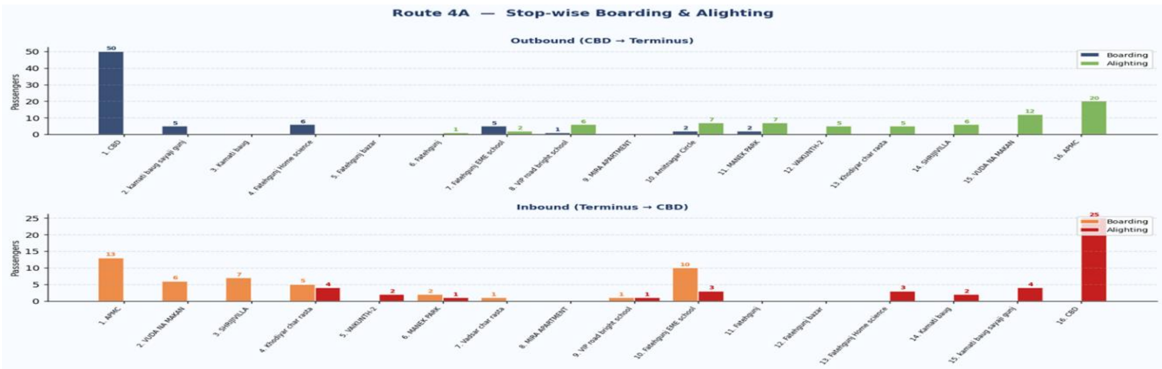

Figure 17: Route 4A – Stop-wise Boarding and Alighting Pattern

The 4A route is characterized by moderate demand concentration with a slightly better distribution than other routes but a large percentage of the stops is underutilized.

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Figure 18: Route 7 – Stop-wise Boarding and Alighting Pattern

Demand is extremely skewed in route 7, with a small number of stops serving most of the demand. This means that there is low stop-level efficiency and route restructuring or stop consolidation is necessary.

4.3.1 Directional Imbalance Analysis

Directional imbalance along routes was then tested to determine the load distribution in both outbound and inbound routes.

Table 5: Directional Imbalance Analysis and Scheduling Priority

DIRECTIONAL IMBALANCE ANALYSIS — ALL ROUTES								
Route	Outbound Boarding	Inbound Boarding	Difference (Out - In)	Imbalance Ratio	Category	Empty Seat Estimate	Scheduling Recommendation	Priority
4	68	18	50	3.78	Severe Outbound	100	Shift 35% inbound slots to outbound peak AM; add PM return trips	URGENT
27	76	21	55	3.62	Severe Outbound	110	Shift 35% inbound slots to outbound peak AM; add PM return trips	URGENT
10	49	17	32	2.88	Severe Outbound	64	Shift 35% inbound slots to outbound peak AM; add PM return trips	URGENT
23	53	19	34	2.79	Severe Outbound	68	Shift 35% inbound slots to outbound peak AM; add PM return trips	URGENT
7	38	15	23	2.53	Severe Outbound	46	Shift 35% inbound slots to outbound peak AM; add PM return trips	URGENT
27A	45	20	25	2.25	High Outbound	50	Add 2–3 inbound trips at peak hours; review timetable	HIGH
13A	54	27	27	2.00	High Outbound	54	Add 2–3 inbound trips at peak hours; review timetable	HIGH
9B	71	39	32	1.82	High Outbound	64	Add 2–3 inbound trips at peak hours; review timetable	HIGH
31	53	30	23	1.77	High Outbound	46	Add 2–3 inbound trips at peak hours; review timetable	HIGH
11	39	23	16	1.70	High Outbound	32	Add 2–3 inbound trips at peak hours; review timetable	HIGH
19A	94	56	38	1.68	High Outbound	76	Add 2–3 inbound trips at peak hours; review timetable	HIGH
4A	71	45	26	1.58	High Outbound	52	Add 2–3 inbound trips at peak hours; review timetable	HIGH
22	66	44	22	1.50	Moderate Outbound	44	Minor rebalancing; monitor quarterly	MEDIUM
3C	107	88	19	1.22	Balanced	38	Well balanced; maintain current schedule	LOW
15	50	44	6	1.14	Balanced	12	Well balanced; maintain current schedule	LOW
17A	62	55	7	1.13	Balanced	14	Well balanced; maintain current schedule	LOW
12	54	59	-5	0.92	Balanced	10	Well balanced; maintain current schedule	LOW
30	43	47	-4	0.92	Balanced	8	Well balanced; maintain current schedule	LOW
8	41	57	-16	0.72	Moderate Inbound	32	Add outbound morning trips; inbound trips can be reduced slightly	MEDIUM
9D	47	68	-21	0.69	Moderate Inbound	42	Add outbound morning trips; inbound trips can be reduced slightly	MEDIUM
18	39	59	-20	0.66	Moderate Inbound	40	Add outbound morning trips; inbound trips can be reduced slightly	MEDIUM
9A	48	77	-29	0.62	Moderate Inbound	58	Add outbound morning trips; inbound trips can be reduced slightly	MEDIUM
26B	40	75	-35	0.53	Moderate Inbound	70	Add outbound morning trips; inbound trips can be reduced slightly	MEDIUM
23D	8	18	-10	0.44	High Inbound	20	Severe inbound dominance; major schedule restructuring needed	URGENT
10D	16	45	-29	0.36	High Inbound	58	Severe inbound dominance; major schedule restructuring needed	URGENT

The analysis indicates a high imbalance in a number of routes, with a number of routes classified as severe or high outbound dominance. This implies the customer demand is very skewed in a single direction especially during the peak seasons, hence resulting in inefficiency in the use of the vehicles as well as wasted returns.

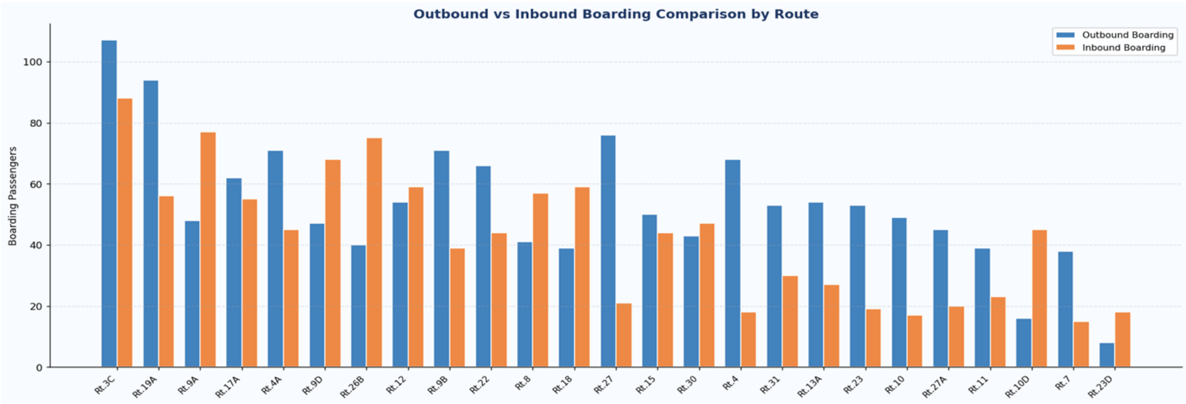

Figure 19: Outbound vs Inbound Boarding Comparison by Route

The comparison vividly shows that there are differences in the number of passengers being carried in each direction, which supports the directional imbalance in the network.

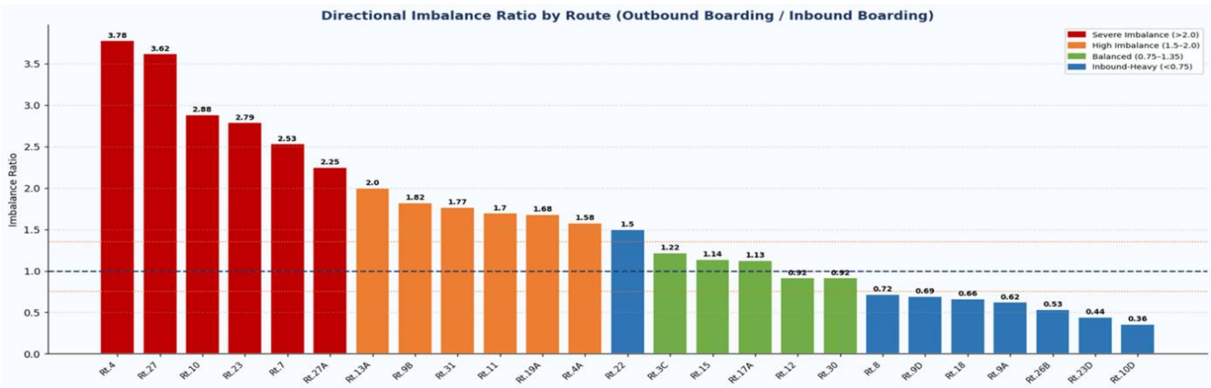

Figure 20: Directional Imbalance Ratio by Route

The ratio of the imbalance between routes that are highly imbalanced, more than 1, signifies outbound dominance and values less than 1 signify inbound dominance. Some of the routes are not within the balanced range, which affirms ineffective scheduling and route planning.

4.3.2 Route Length and Demand Relationship

The correlation between the route length and the total number of passengers was used to determine whether the route design was in line with demand.

The distribution of public transport demand at the ward level reveals significant spatial disparities in public transport demand in the city.

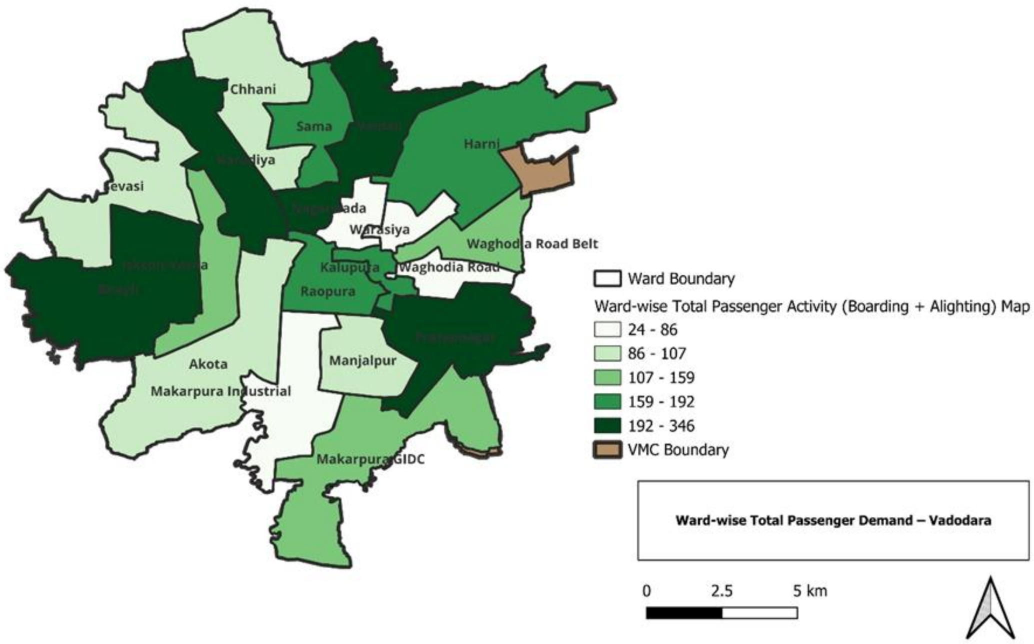

Figure 21: Ward-wise Total Passenger Demand Distribution within VMC

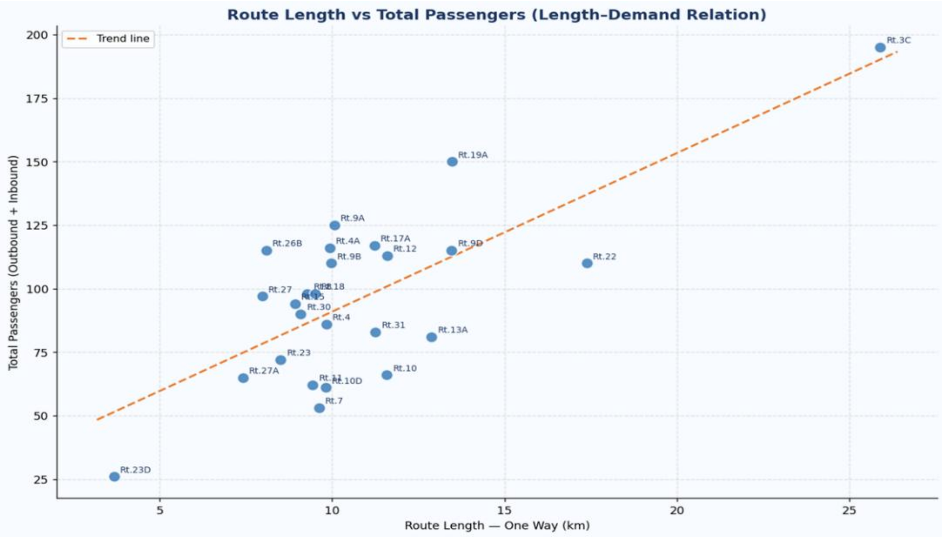

Figure 22: Route Length vs Total Passengers (Length–Demand Relationship)

The inconsistency in network planning is further verified by the relationship between the length of routes and the demand. In general, the network has low stop productivity and uneven utilization that requires restructuring of its routes and demand responsive planning.

4.4 IPT and Last-Mile Connectivity Analysis

IPT is very important in closing accessibility gaps in the transport system.

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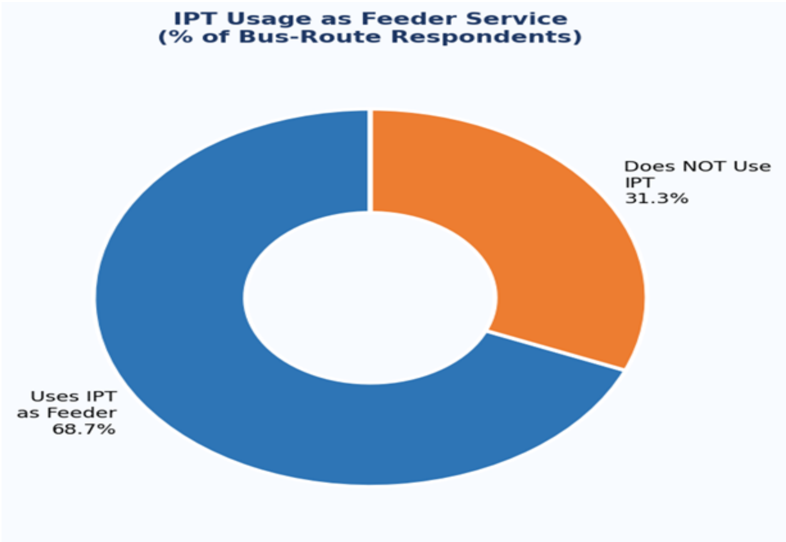

Figure 23: IPT Usage as Feeder Service (% of Bus Route Respondents)

Most of the respondents (68.7%) use IPT as a feeder mode thus its significant role in facilitating access to bus services.

The distance to bus stops and unfavorable walking conditions are found to have a significant impact on IPT dependency, as a compensatory mechanism in response to poor accessibility.

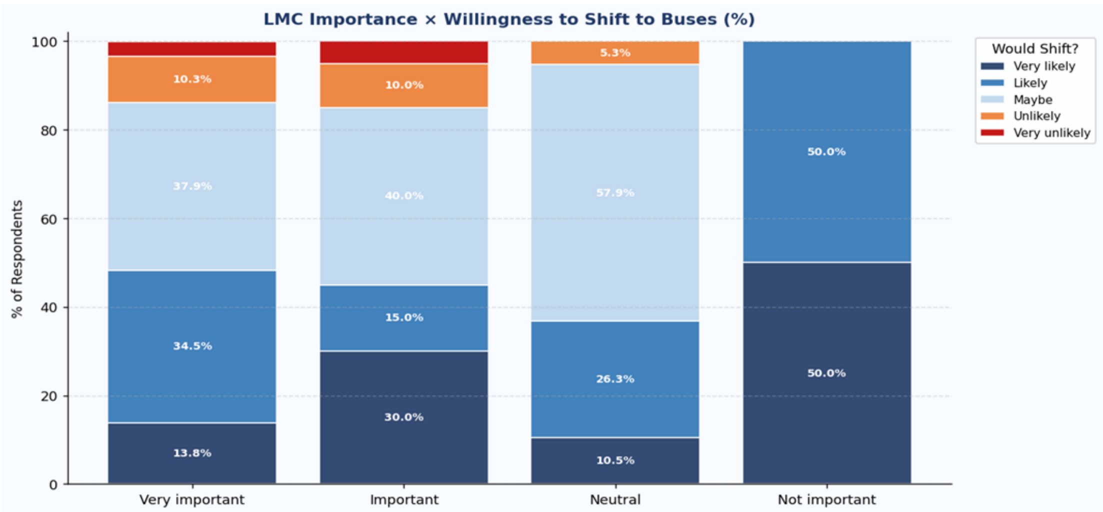

Figure 24: Last-Mile Connectivity Importance vs Willingness to Shift to Buses (%)

There is a close association between the perceived significance of last-mile connectivity and readiness to switch to bus usage, which once again supports its role as a key determinant of modal choice.

Table 6: Barriers to IPT Usage and Planning Implications

Reason	Percentage	Planning Implication
Prefer private vehicle	44.4%	Barrier behavioural; needs demand management strategies.
Safety concerns	16.7%	Require controlled and secure IPT practices.

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Limited availability	16.7%	Gap in supply side; feeder service integration is required.
High cost	11.1%	Fare integration and subsidy mechanisms needed.
Bus stop within walking distance	11.1%	Shows satisfactory access in restricted regions.

The preference of the behaviour towards the use of private vehicles, safety, lack of availability and cost hinders effective IPT use. Lack of formal integration between IPT and bus systems makes it less efficient and less appealing as a multimodal travel mode.

Altogether, IPT is not just an auxiliary mode but a critical element of the system of urban transport. Its successful incorporation in terms of organised feeder services, fare coordination, and better pedestrian infrastructure is vital in improving system performance, and modal shift.

4.5 Discussion and Planning Implications

This combined analysis indicates that the shortcomings of the bus system are largely structural as opposed to demand-related. Spatial inefficiencies, where services are concentrated along major corridors and where coverage is inadequate in the peripheral areas, limit accessibility and reduce the potential to ridership. Strategic failures in operational efficiency, such as the distribution of passengers and directional imbalance, also limit the performance of the system.

Overlay analysis also shows that a number of residential and mixed-use areas still exist in bus service gap zones.

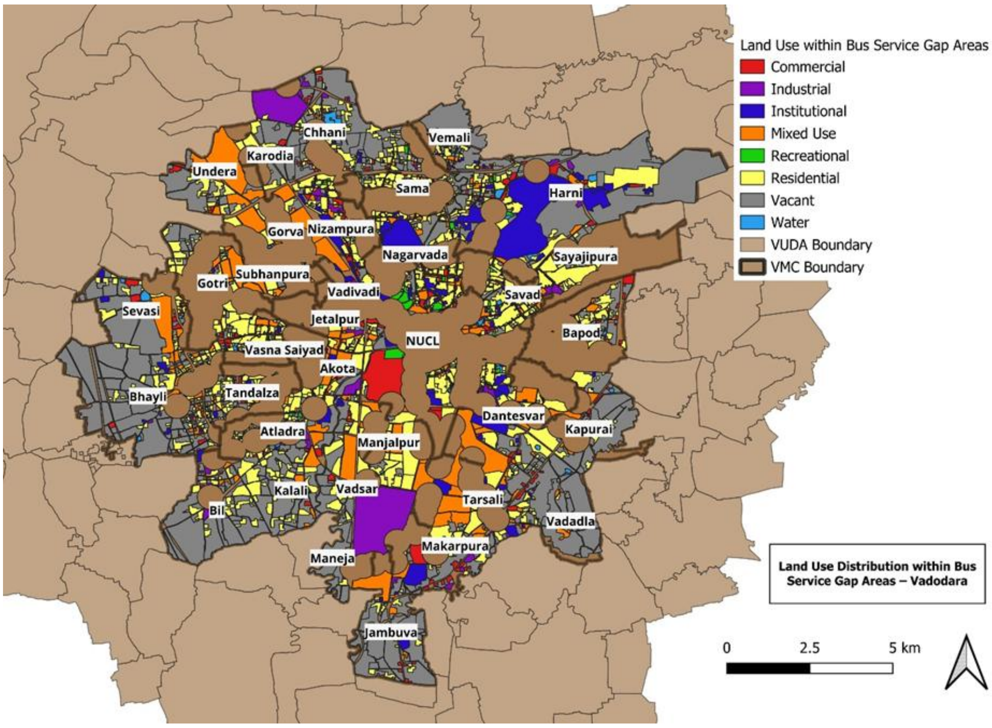

Figure 25: Land Use Distribution within Bus Service Gap Areas – Vadodara

Limitations on accessibility, especially long pedestrian distances, inadequate pedestrian infrastructure, and weak last-mile connectivity become important barriers to usage. Simultaneously, the absence of formal integration between buses and IPT minimizes the effectiveness and reliability of multimodal transport.

These results show that to enhance public transport in Vadodara, it is necessary to have a holistic and integrated approach. The priority interventions include demand-responsive network restructuring, improving service frequency and reliability of services, improving pedestrian infrastructure, and formal integration of IPT as a feeder system. To tap into the hidden demand and reduce dependence on private vehicles, it is important to align service delivery with prevailing travel patterns, especially work and learning trips.

All in all, the findings show that the sustainability of urban mobility in Vadodara can be attained through the coordination of interventions aimed at optimizing the networks, increasing their accessibility, and integrating them on a multimodal basis.

5. Conclusion and Recommendations

This study assessed the performance of the Vadodara bus transport system using travel behaviour analysis, spatial accessibility analysis and operational network performance analysis. The results show that while the city has strong demand for public transport services, namely for work and education-related trips, this potential is not fully realized due to the limitations of the existing bus services.

A number of structural issues were identified in the system that impact its operational performance such as limited-service coverage in the periphery, poor first- and last-mile connectivity, uneven passenger distribution across routes, directional operational imbalances and lack of pedestrian infrastructure. These constraints limit the reliability and accessibility of services, and promote reliance on private vehicles even though there are many trips that are appropriate for public transport. The study also emphasises the importance of Intermediate Public Transport (IPT) to provide first- and last-mile connectivity. However, its limited integration with the formal bus network, therefore, travel costs increase and the efficiency of multimodal transportation is reduces the efficiency.

The study suggests demand-responsive network restructuring, increase service frequency, upgrade pedestrian infrastructure, formalize IPT as a feeder service, develop multimodal interchange, data-driven service planning and integrated fare policies to enhance operational efficiency and accessibility. Implementing these measures can contribute to a more balanced use of urban transport modes, reduce the need for private vehicles, and promote a more inclusive, efficient, and sustainable transportation system in urban areas.

While the study provides valuable insights about optimizing bus service, its findings are constrained by the lack of real-time operational data, an analysis of dynamic scheduling and economic analysis of recommended interventions. Future research could incorporate operational datasets, such as those provided by GPS, intelligent transport systems, demand forecasting techniques, and simulation-based optimization models to improve evidence-based public transport planning in medium-sized cities.

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