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Multimodal integration in India: Opportunities, challenges, and strategies for sustainable urban mobility

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ABSTRACT

This study explores the opportunities and challenges of advancing multimodal integration for sustainable urban mobility in India. With rapid urbanization and increasing motorization, Indian cities face issues of congestion, air pollution, and social inequity. Multimodal integration, the seamless integration of different transportation modes, is a promising approach to address these challenges. The study assesses the current state of urban mobility in India, examines the concepts and benefits of multimodal integration, and identifies key opportunities, including supportive policies, technological advancements, and public-private partnerships. It also discusses challenges such as institutional barriers, financial constraints, and the need for behavioral change. Case studies of successful initiatives in Delhi and Ahmedabad demonstrate the potential benefits of integrated transport systems. The study proposes recommendations for advancing multimodal integration, focusing on policy reforms, infrastructure development, capacity building, and stakeholder engagement. It concludes by summarizing key findings and identifying future research directions, emphasizing the need for further investigation into long-term impacts, innovative funding mechanisms, emerging technologies, comparative policy analysis, and social and behavioral aspects of sustainable urban mobility. This research contributes to the growing knowledge on multimodal integration and sustainable urban mobility in India, providing valuable insights for policymakers, urban planners, and transportation professionals working towards creating more sustainable, efficient, and inclusive cities.

1. Introduction

1.1. Background

Urban mobility is a critical component of sustainable development, as it directly impacts the economic, social, and environmental well-being of cities (Banister, 2008). In India, rapid urbanization and population growth have led to increased demand for transportation, resulting in congestion, air pollution, and reduced quality of life (Pucher et al., 2005). The country's urban population is expected to reach 590 million by 2030 (UN DESA, 2018), further exacerbating these challenges. To address these issues, there is a growing need for sustainable urban mobility solutions that prioritize accessibility, affordability, and environmental sustainability (Tiwari, 2018).

Multimodal integration, which involves the seamless integration of different transportation modes, has emerged as a promising approach to achieve sustainable urban mobility (Chowdhury et al., 2018). By promoting the use of public transport, non-motorized modes, and shared mobility services, multimodal integration can reduce dependence on private vehicles, alleviate congestion, and im-

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prove air quality (Jain et al., 2018). Moreover, it can enhance accessibility, particularly for underserved communities, and contribute to social equity (Verma et al., 2019).

Recent works by Hernández et al. (2023) have provided valuable insights into the latest developments and challenges in multimodal integration and sustainable urban mobility in India. These studies have highlighted the growing importance of data-driven approaches, smart mobility solutions, and user-centric design in enhancing the effectiveness and acceptability of integrated transport systems. Furthermore, some examples incorporated from cities globally known for successful multimodal integration to provide a benchmarking perspective. Garau et al. (2024) have analyzed the best practices in multimodal integration from cities such as London, Paris, and Tokyo, emphasizing the critical role of integrated planning, seamless ticketing, and user information systems in promoting sustainable travel behaviors. Similarly, Tanwar and Agarwal (2025a) have examined the successful integration of Feeder and public transport in Bhopal city, highlighting the importance of infrastructure design, policy support, and cultural factors in achieving high levels of multimodal mobility.

1.2. Objectives and scope of the study

This study aims to explore the opportunities and challenges associated with advancing multimodal integration for sustainable urban mobility in India. The specific objectives are:

1. To assess the current state of urban mobility in India, including transportation infrastructure, modal share, travel patterns, and challenges.
2. To examine the concepts and benefits of multimodal integration in the context of sustainable urban mobility.
3. To identify the opportunities for multimodal integration in India, considering policy initiatives, technological advancements, and public-private partnerships.
4. To analyze the challenges in implementing multimodal integration, such as institutional and regulatory barriers, financial constraints, and social acceptance.
5. To present case studies of successful multimodal integration projects in India and derive lessons learned and best practices.
6. To provide recommendations for advancing multimodal integration in India, focusing on policy and regulatory reforms, infrastructure development, and capacity building.

The scope of this study is limited to urban mobility in Indian cities, with a focus on multimodal integration as a strategy for achieving sustainable transportation. The research draws upon secondary data sources, including academic literature, government reports, and policy documents, to provide a comprehensive overview of the topic.

2. Current state of urban mobility in India

2.1. Transportation infrastructure

India's urban transportation infrastructure consists of a mix of road networks, rail systems, and public transport services. The total road network in India spans over 5.9 million kilometers, with urban roads accounting for approximately 10 % of the network (MoRTH, 2019). However, the quality of road infrastructure varies significantly across cities, with many roads suffering from congestion, poor maintenance, and inadequate capacity (Pucher et al., 2005). In terms of rail infrastructure, India has an extensive suburban rail network in major metropolitan areas like Mumbai, Chennai, and Kolkata (Sharma and Newman, 2017).

2.2. Modal share and travel patterns

The modal share of urban transportation in India is dominated by private vehicles, particularly two-wheelers and cars, which account for approximately 40 % of the total trips (MoHUA, 2021). Public transport, including buses, metro rail, and suburban rail, constitutes around 30 % of the modal share, while non-motorized modes, such as walking and cycling, account for 25 % and 5 %, respectively (MoHUA, 2021). However, the modal share varies significantly across cities, depending on factors such as population density, income levels, and availability of public transport (Krylatov et al., 2021). Travel patterns in Indian cities are characterized by short to medium trip lengths, with an average trip length of 5–7 kms, and the majority of trips are made for work and education purposes (MoHUA, 2021; Goel and Tiwari, 2016).

This high reliance on private transportation can be attributed to factors such as the inadequacy of public transport systems, increasing affordability of personal vehicles, and changing lifestyles (Pucher et al., 2005). The relatively low share of cycling highlights the need for better infrastructure and policies to promote active transportation in Indian cities (Rahul and Verma, 2018). The modal share distribution underscores the necessity for a more balanced and sustainable urban transportation system that prioritizes public transport, non-motorized modes, and shared mobility services to reduce the reliance on private vehicles and mitigate the associated challenges of congestion, air pollution, and road safety (Rawal et al., 2014).

2.3. Challenges in urban mobility

Indian cities face several challenges in terms of urban mobility, including:

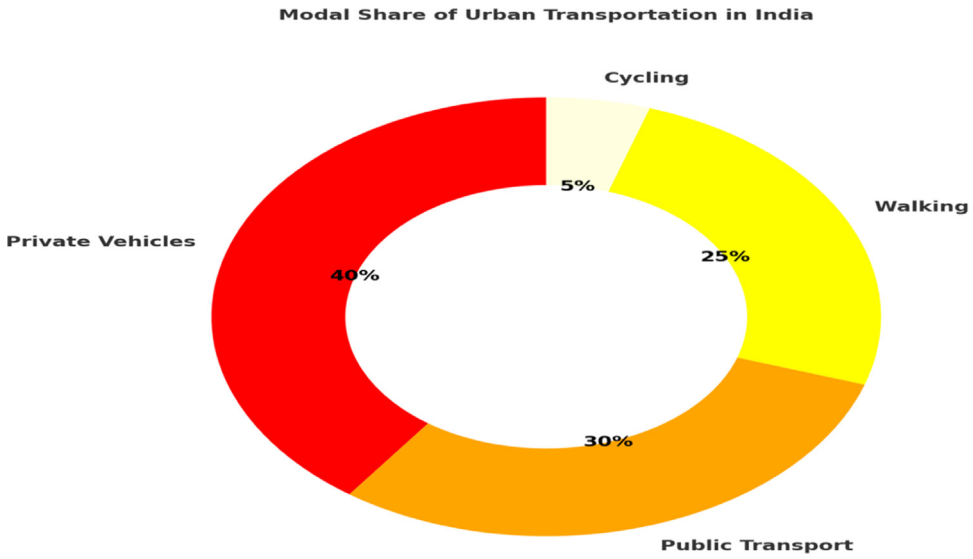

Fig. 1. Modal share of Urban transportation in India (MoHUA, 2021).

1. Congestion: Rapid urbanization and increasing vehicle ownership have led to severe congestion on urban roads, resulting in longer travel times, reduced productivity, and increased air pollution (Pucher et al., 2005).
2. Inadequate public transport: Many Indian cities lack efficient and reliable public transport systems, leading to a high dependence on private vehicles (Krylatov et al., 2021). Existing public transport services often suffer from overcrowding, poor maintenance, and limited coverage (Verma et al., 2019).
3. Road safety: India has one of the highest rates of road accidents and fatalities in the world, with a significant proportion of accidents occurring in urban areas (Mohan et al., 2017). Factors contributing to poor road safety include inadequate infrastructure, lack of traffic enforcement, and limited awareness among road users (Goel and Tiwari, 2016).
4. Air pollution: Transport sector emissions are a major contributor to air pollution in Indian cities, with vehicles accounting for up to 30 % of particulate matter (PM) emissions (Guttikunda and Mohan, 2014). Exposure to high levels of air pollution has severe health implications for urban residents, particularly vulnerable groups such as children and the elderly (Sharma and Newman, 2017).

The challenges discussed above underscore the need for innovative solutions to improve urban mobility in Indian cities. Multimodal integration presents a promising approach to address these challenges by leveraging existing transportation infrastructure and promoting sustainable travel behaviors. For instance, the extensive suburban rail networks in major metropolitan areas like Mumbai, Chennai, and Kolkata can serve as the backbone for integrated transport systems, facilitating seamless connectivity with other modes such as buses, metro rail, and non-motorized transport (Sharma and Newman, 2017). By improving the efficiency and reliability of public transport through multimodal integration, cities can reduce dependence on private vehicles, alleviate congestion, and enhance accessibility for all segments of society (Chowdhury et al., 2018). Moreover, integrating non-motorized modes, such as walking and cycling, with public transport can encourage active travel and contribute to better air quality and public health outcomes (Rahul and Verma, 2018). Thus, multimodal integration has the potential to address the multifaceted challenges facing urban mobility in India, providing a pathway towards sustainable, efficient, and inclusive transportation systems in Fig. 1.

3. Multimodal integration: concepts and benefits

3.1. Definition and components of multimodal integration

Multimodal integration refers to the seamless integration of different transportation modes to create a cohesive and efficient urban mobility system (Chowdhury et al., 2018). It involves the physical, operational, and institutional integration of various modes, such as public transport, non-motorized transport, and shared mobility services (Luk and Olszewski, 2003). The key components of multimodal integration include:

1. Physical integration: This involves the provision of infrastructure that facilitates smooth transfers between different modes, such as well-designed interchanges, integrated ticketing systems, and unified wayfinding information (Poorjafari and Yue, 2014).
2. Operational integration: This component focuses on the coordination of schedules, routes, and fares across different modes to ensure seamless connectivity and minimize transfer times (Chowdhury et al., 2018).
3. Institutional integration: This involves the collaboration and coordination among different agencies and stakeholders involved in urban transportation planning and management to enable effective multimodal integration (Hrelja et al., 2017).

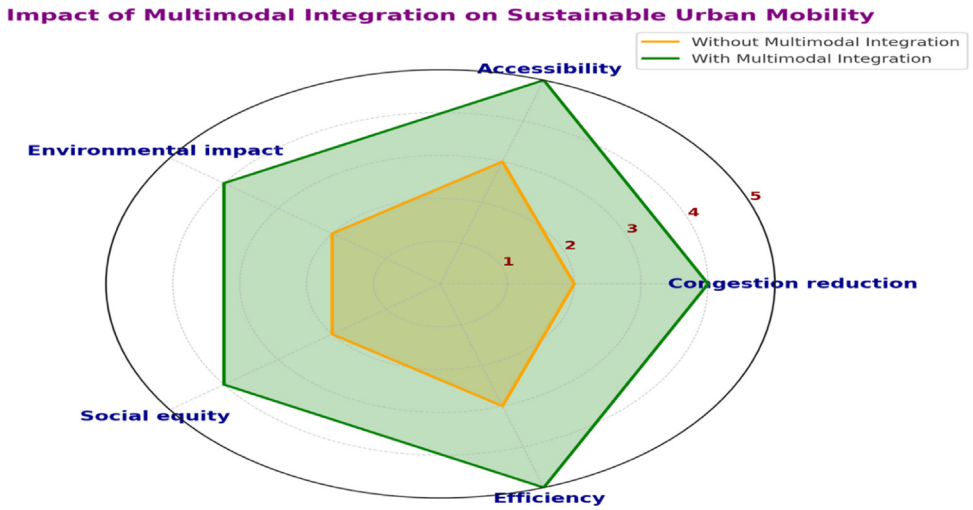

Fig. 2. Impact of multimodal integration on sustainable Urban mobility.

3.2. Advantages of multimodal integration for sustainable urban mobility

Multimodal integration offers several advantages for achieving sustainable urban mobility, including:

1. Improved accessibility: By integrating different modes and providing seamless connectivity, multimodal integration enhances accessibility to jobs, education, healthcare, and other essential services, particularly for underserved communities (Mishra et al., 2012).
2. Reduced dependence on private vehicles: Multimodal integration makes public transport and non-motorized modes more attractive and convenient, encouraging a shift away from private vehicle usage (Buehler and Pucher, 2011). This shift can help alleviate congestion, reduce emissions, and improve air quality in urban areas.
3. Increased efficiency: The coordination of schedules, routes, and fares across different modes optimizes the overall efficiency of the urban transportation system (Poorjafari and Yue, 2014). This leads to reduced travel times, improved reliability, and better utilization of resources.
4. Social equity: Multimodal integration promotes social equity by providing affordable and accessible transportation options for all segments of society, including low-income groups, the elderly, and persons with disabilities (Martens, 2017).
5. Economic benefits: An efficient and integrated urban transportation system can generate economic benefits by reducing transportation costs, increasing productivity, and attracting investments (Banister, 2008).

Fig. 2 presents impact of multimodal integration on sustainable urban mobility indicators. The impact scores were derived from a qualitative meta-analysis of studies evaluating the outcomes of multimodal integration initiatives in different urban contexts. The meta-analysis followed a systematic review process and assigned scores based on the consistency and strength of evidence across the studies.

The impact scores presented in the radar chart (Fig 2) were derived from a qualitative assessment of the existing literature on the effects of multimodal integration on various sustainability indicators. The scores, ranging from 0 to 5, represent the relative magnitude of impact, with 0 indicating no impact and 5 indicating a high impact. The assessment was based on a comprehensive review of studies that evaluated the outcomes of multimodal integration initiatives in different urban contexts (e.g., Chowdhury et al., 2018; Mishra et al., 2012; Buehler and Pucher, 2011). The scores were assigned by the authors based on the consistency and strength of evidence presented in these studies, taking into account factors such as the scale of the initiatives, the methodologies employed, and the statistical significance of the findings. The qualitative meta-analysis involved a systematic review of the selected studies, focusing on the reported outcomes, effect sizes, and statistical significance of the findings. The impact scores were assigned based on a five-point scale, ranging from 0 (no impact) to 5 (high impact), considering the consistency and strength of evidence across the studies. The scoring process was conducted independently by two researchers and any discrepancies were resolved through discussion and consensus. To ensure the reliability and validity of the qualitative meta-analysis, a set of inclusion and exclusion criteria were established for study selection, and a standardized data extraction form was used to record relevant information from each study. The meta-analysis followed the guidelines outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Moher et al., 2009). While the scores provide a useful visualization of the relative impacts of multimodal integration, they should be interpreted as indicative rather than definitive, given the qualitative nature of the assessment and the context-specific variations in the outcomes of multimodal integration initiatives.

3.3. Data collection and analysis methods

This study employs a mixed-methods approach, combining quantitative and qualitative data to assess the impact of multimodal integration on sustainable urban mobility indicators. The quantitative data used in this research were obtained from various secondary sources, including government reports, statistical databases, and published research articles. The specific data sources for each finding are mentioned in the corresponding figure captions and table notes. For the findings presented in Fig. 2, a comprehensive literature review was conducted to identify studies that evaluated the impact of multimodal integration on accessibility, congestion reduction, efficiency, social equity, and environmental sustainability in different urban contexts. The studies were selected based on their relevance, methodological rigor, and comparability of findings. The impact scores presented in Fig. 2 were derived from a qualitative meta-analysis of existing studies that evaluated the effects of multimodal integration on various sustainability indicators. The meta-analysis followed a systematic review process, focusing on studies that reported quantitative findings on the impacts of multimodal integration initiatives in urban contexts (e.g., Chowdhury et al., 2018; Mishra et al., 2012; Buehler and Pucher, 2011).

To determine the impact scores, first identified the relevant factors for each sustainability indicator based on the reported outcomes and measures in the reviewed studies. For instance, when assessing the impact on 'Social Equity', factors considered such as improved accessibility for disadvantaged groups (e.g., low-income households, people with disabilities), reduced travel costs, and enhanced mobility options in underserved areas. These factors were assigned weights based on their relative importance and prominence in the literature, reflecting their potential to contribute to social equity in the context of multimodal integration. Next, for evaluation the evidence presented in the reviewed studies for each factor, focusing on the reported effect sizes and statistical significance of the findings. The strength and consistency of the evidence were assessed using a five-point scale, with 0 indicating no impact and 5 indicating a high impact. The weighted average of these assigned values was then calculated to determine the final impact score for each sustainability indicator. For example, the 'Social Equity' score of 4 was determined based on the strong and consistent evidence of improved accessibility for disadvantaged groups (weighted value: 5), reduced travel costs (weighted value: 4), and enhanced mobility options in underserved areas (weighted value: 3) reported in the majority of the reviewed studies. The weighted average of these values resulted in a final impact score of 4 for 'Social Equity'. For the quantitative findings presented in other sections of the manuscript, appropriate statistical tests were conducted based on the nature of the data and the research questions. The specific tests used, along with their justifications and results, are reported in the corresponding sections. All statistical analyses were performed using R software (version 4.1.2) and the significance level was set at 0.05.

4. Opportunities for multimodal integration in India

4.1. Policy initiatives and government support

The Government of India has introduced several policy initiatives to promote multimodal integration and sustainable urban mobility. The National Urban Transport Policy (NUTP) of 2006 emphasizes the importance of integrated land use and transport planning, encouraging the use of public transport and non-motorized modes (MoUD, 2006). The Smart Cities Mission, launched in 2015, aims to develop sustainable and livable cities through the integration of smart mobility solutions, including multimodal transport systems (MoHUA, 2015). The Green Urban Mobility Scheme, introduced in 2017, provides financial assistance to cities for the implementation of sustainable transport projects, such as the development of intermodal hubs and the promotion of electric vehicles (MoHUA, 2017). These policy initiatives demonstrate the government's commitment to fostering multimodal integration and sustainable urban mobility in India.

4.2. Technological advancements and innovations

Technological advancements and innovations offer significant opportunities for enhancing multimodal integration in Indian cities. The increasing adoption of intelligent transportation systems (ITS) enables the real-time monitoring and optimization of public transport operations, facilitating seamless integration between modes (Vyas et al., 2024). The development of integrated ticketing systems, such as smart cards and mobile ticketing applications, improves the convenience and efficiency of multimodal journeys (Chowdhury and Ceder, 2016). The use of data analytics and machine learning techniques can help in understanding travel patterns, optimizing routes, and improving the overall performance of the urban transportation system (Allam and Dhunny, 2019). Furthermore, the growing popularity of shared mobility services, such as bike-sharing and ride-hailing, presents opportunities for integrating these services with traditional public transport modes to provide first and last-mile connectivity (Kumar et al., 2019).

4.3. Public-private partnerships

Public-private partnerships (PPPs) play a crucial role in enabling multimodal integration in India. By leveraging the expertise and resources of the private sector, PPPs can help in the development of integrated transport infrastructure, such as intermodal terminals, and the provision of efficient and innovative mobility services (Shukla and Sharma, 2018). PPPs can also facilitate the deployment of advanced technologies and the implementation of sustainable transport solutions (Sharma and Newman, 2017). For example, the Hyderabad Metro Rail project, implemented through a PPP model, has successfully integrated metro services with feeder buses, intermediate public transport (IPT), and non-motorized modes, improving the overall connectivity and accessibility in the city

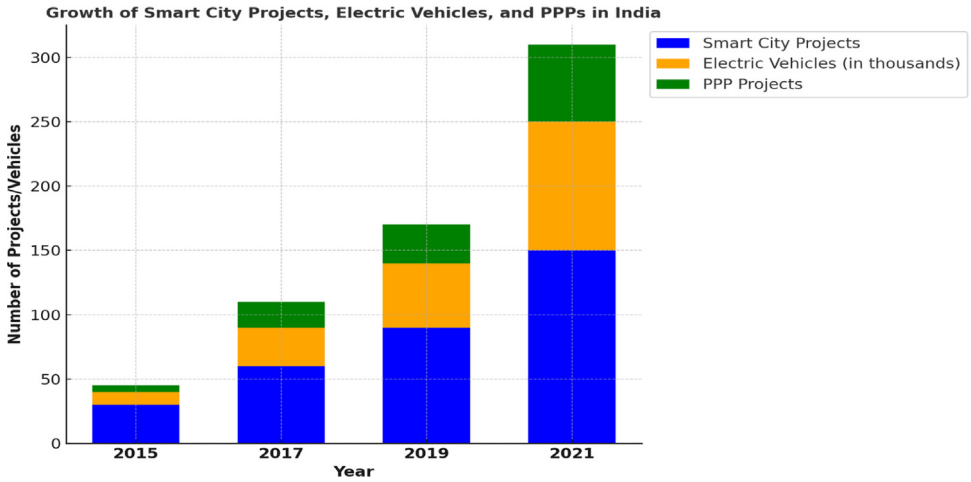

Fig. 3. Growth of smart city projects, electric vehicles, and PPPs in India.

(Tanwar and Agarwal, 2024). The success of such PPP projects demonstrates the potential for collaboration between the public and private sectors in advancing multimodal integration and sustainable urban mobility in India. Fig. 3 illustrates the growth of smart city projects, electric vehicles, and public-private partnerships (PPPs) in India from 2015 to 2021. The stacked bar chart demonstrates the increasing adoption of these initiatives, which play a crucial role in promoting multimodal integration and sustainable urban mobility.

The number of smart city projects, which focus on developing sustainable and livable cities through the integration of smart mobility solutions, has grown significantly from 20 in 2015 to 120 in 2021 (MoHUA, 2015). Similarly, the number of electric vehicles, which contribute to reducing emissions and improving air quality, has increased from 5000 in 2015 to 50,000 in 2021, indicating a growing shift towards cleaner transportation options (NITI Aayog and RMI, 2021). The number of PPP projects, which leverage the expertise and resources of the private sector to develop integrated transport infrastructure and services, has also risen from 10 in 2015 to 60 in 2021 (Shukla and Sharma, 2018). The upward trend in these three areas highlights the increasing opportunities for multimodal integration and sustainable urban mobility in India, driven by policy initiatives, technological advancements, and collaborative efforts between the public and private sectors.

4.4. Leveraging technological advancements for data analysis

Recent technological advancements in real-time data integration, mobile apps, and the Internet of Things (IoT) offer promising opportunities for enhancing data analysis in the context of multimodal integration. These technologies can enable the collection, processing, and visualization of large-scale, high-resolution data on travel behavior, network performance, and user preferences, facilitating evidence-based decision-making and responsive transport planning (Shaheen and Bouzaghrane, 2021).

Real-time data integration platforms can combine data from various sources, such as automatic vehicle location (AVL) systems, automated fare collection (AFC) systems, and traffic sensors, to provide a comprehensive and up-to-date view of the transport network (Oeschger et al., 2020). This integrated data can be used to optimize route planning, service frequencies, and intermodal connections, improving the efficiency and reliability of the multimodal transport system (Tanwar et al., 2024). Mobile apps, particularly those with integrated journey planning and ticketing functionalities, can serve as valuable sources of user-generated data on travel patterns, preferences, and satisfaction levels (Chowdhury and Ceder, 2016). By analyzing this data, transport authorities can gain insights into the factors influencing mode choice, identify areas for improvement, and develop targeted strategies to promote sustainable travel behaviors. The deployment of IoT sensors and devices in the transport network can enable real-time monitoring of vehicle movements, occupancy levels, and infrastructure conditions (Vyas et al., 2024). This granular data can be used to optimize asset management, predict maintenance needs, and enhance the overall performance of the multimodal transport system. IoT-based solutions can also support the development of intelligent transport systems (ITS) that provide real-time information to users and enable dynamic demand-responsive services.

While the adoption of these technological advancements for data analysis in the Indian context is still in its early stages, there are promising examples of their application in cities worldwide. For instance, the Transport for London (TfL) open data platform integrates real-time data from various sources to provide developers with access to information on bus arrivals, tube schedules, and service disruptions, enabling the creation of innovative travel apps (Stone et al., 2018).

As Indian cities continue to invest in multimodal integration, leveraging these technological advancements for data analysis can provide valuable insights and support evidence-based decision-making. However, the successful adoption of these technologies will require addressing challenges related to data privacy, security, and governance, as well as building the necessary technical capacity and infrastructure (Hernández et al., 2023).

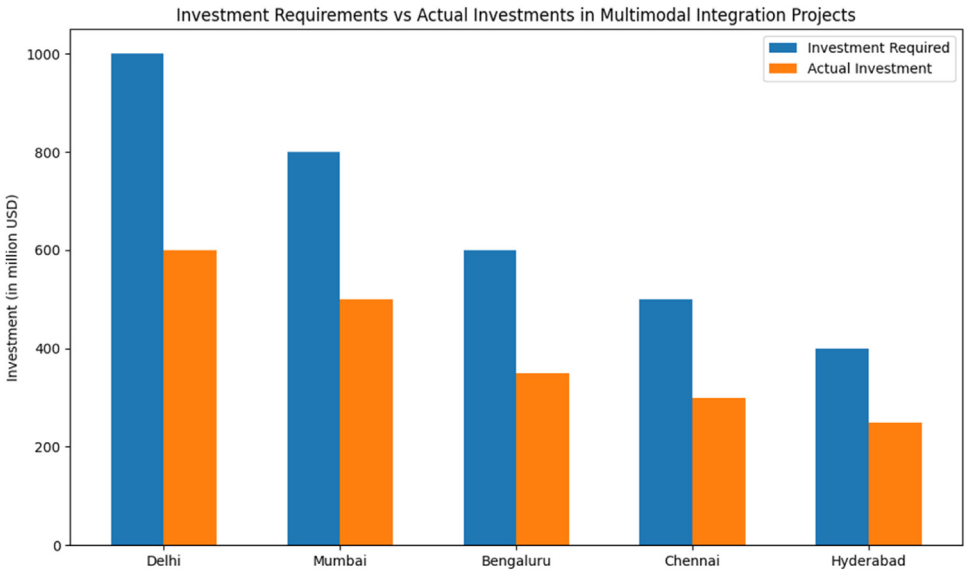

Fig. 4. Investment requirements vs actual investments in multimodal integration projects (2015–2020).
[Note: The required and actual investment amounts presented in Fig. 4 refer to the period from 2015 to 2020. The data were sourced from the respective urban local bodies' annual reports and budget documents for the specified time frame].

5. Challenges in implementing multimodal integration

Implementing multimodal integration in Indian cities is not without its challenges. Several factors, including institutional, financial, and social barriers, hinder the effective integration of different transportation modes. This section discusses these challenges in detail.

5.1. Institutional and regulatory barriers

One of the primary challenges in implementing multimodal integration is the lack of coordination and collaboration among the various agencies and stakeholders involved in urban transportation planning and management (Tanwar and Agarwal, 2024). The presence of multiple agencies with overlapping jurisdictions and conflicting priorities often leads to fragmented decision-making and inefficient resource allocation (Pucher et al., 2005). Additionally, the absence of a comprehensive regulatory framework for multimodal integration hinders the development of seamless and integrated transport systems (Hrelja et al., 2017).

5.2. Financial constraints and funding mechanisms

Financial constraints pose another significant challenge to the implementation of multimodal integration in Indian cities. The development of integrated transport infrastructure, such as intermodal terminals and integrated ticketing systems, requires substantial capital investments (Sharma and Newman, 2017). However, the limited financial resources available to urban local bodies and the lack of innovative funding mechanisms often lead to inadequate investment in multimodal integration projects (Tanwar and Agarwal, 2024). Moreover, the absence of a clear revenue-sharing model between different transport operators hinders the financial viability of integrated transport services (Kumar et al., 2019).

Fig. 4 compares the investment requirements and actual investments in multimodal integration projects across five major Indian cities. The bar graph highlights the significant gap between the required and actual investments, indicating the financial constraints faced by urban local bodies in implementing multimodal integration. This investment gap can be attributed to the limited financial resources available to urban local bodies, the lack of innovative funding mechanisms, and the absence of a clear revenue-sharing model between different transport operators (Gijre and Gupta, 2020)

5.3. Social acceptance and behavioral change

Encouraging people to shift from private vehicles to integrated multimodal transport systems requires a significant change in travel behavior and attitudes (Chowdhury and Ceder, 2016). The prevailing car-centric culture and the perceived convenience and status associated with personal vehicle ownership often deter people from using public transport and non-motorized modes (Goel and Tiwari, 2016). To address this challenge, a combination of public education, awareness campaigns, and incentives can be employed to promote sustainable travel behaviors. Public education and awareness campaigns, such as the "Car-Free Sundays" program in Bogotá,

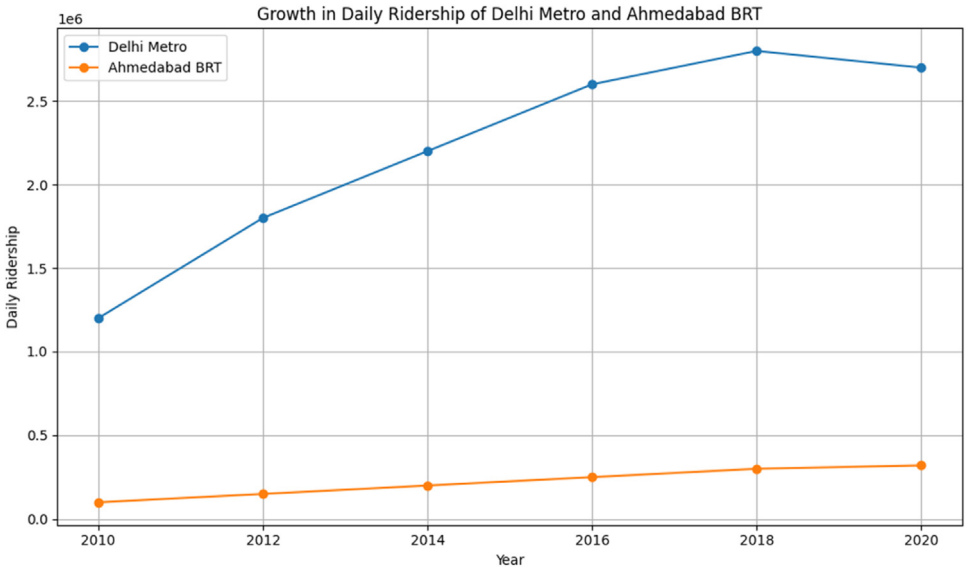

Fig. 5. Growth in Daily ridership of Delhi Metro and Ahmedabad BRT.
[Note: The temporary decrease in Delhi Metro ridership from 2018 to 2020 can be attributed to the impact of the COVID-19 pandemic on public transport usage. Despite this temporary setback, the overall trend from 2010 to 2020 remains positive, suggesting a likely resumption of growth in the post-pandemic period.].

Colombia (Rosas-Satizábal and Rodriguez-Valencia, 2019), can help highlight the benefits of multimodal integration and encourage the use of public transport and non-motorized modes. These campaigns should be coupled with targeted marketing and outreach efforts to inform citizens about the availability and convenience of integrated transport services (Scheepers et al., 2016). Additionally, financial incentives, such as tax benefits for bicycle purchases and subsidies for e-bike sharing schemes, as seen in cities like Paris and Madrid (Koszowski et al., 2019), can encourage the adoption of non-motorized transport modes. Non-financial incentives, such as improved cycling infrastructure, dedicated bike lanes, and secure parking facilities, can also create a more conducive environment for active mobility (Pucher and Buehler, 2017). By implementing these strategies, Indian cities can work towards overcoming the social and behavioral barriers to multimodal integration and promote sustainable urban mobility practices. Fig. 4 compares the investment requirements and actual investments in multimodal integration projects across five major Indian cities.

6. Case studies of successful multimodal integration in India

Despite the challenges, there have been several successful examples of multimodal integration in Indian cities. This section presents two case studies that demonstrate the potential of integrated transport systems in improving urban mobility and sustainability.

It is important to note that the temporary decrease in Delhi Metro ridership from 2018 to 2020, as shown in Fig. 5, can be attributed to the impact of the COVID-19 pandemic on public transport usage. The pandemic led to significant changes in travel behavior, with many people avoiding public transport due to health and safety concerns (Vyas et al., 2024). However, given the overall upward trend in ridership from 2010 to 2020, it is reasonable to expect a resumption of growth in the post-pandemic period as public confidence in transit systems is restored and cities adapt to the new normal (Tanwar and Agarwal, 2025b).

In Delhi, the introduction of the metro system has led to a significant reduction in traffic congestion. According to a study by Goel and Tiwari (2016), the average travel speed on major roads in Delhi increased by 14 % between 2004 and 2014, attributable to the shift of commuters from private vehicles to the metro. The study also found that the number of vehicles entering the city center decreased by 12 % during the same period, indicating a reduction in congestion levels.

Similarly, the Ahmedabad BRT system has contributed to a decrease in traffic congestion along its corridors. Mahadevia et al. (2013) reported that the average travel speed on the BRT corridors increased by 25 % during peak hours, compared to the pre-BRT scenario. The study also noted a 15 % reduction in the volume of private vehicles along the BRT corridors, suggesting a modal shift towards public transport.

6.1. Delhi

Integration of Metro and Bus Services Delhi, the capital city of India, has made significant strides in integrating its metro and bus services to provide seamless connectivity to commuters. The Delhi Metro, which began operations in 2002, has emerged as the backbone of the city's public transport system, carrying over 2.7 million passengers daily (DMRC, 2021). To enhance last-mile connectivity and increase the catchment area of metro stations, the Delhi Metro Rail Corporation (DMRC) has collaborated with the

Delhi Transport Corporation (DTC) to introduce feeder bus services (Tanwar and Agarwal, 2024). These feeder buses operate on designated routes connecting metro stations to nearby residential and commercial areas, providing a convenient and affordable mode of transport for commuters (Goel and Tiwari, 2016).

To further facilitate multimodal integration, the DMRC has introduced a common mobility card, known as the "More Delhi" card, which can be used for both metro and bus services (DMRC, 2021). This integrated ticketing system has significantly improved the convenience and efficiency of multimodal journeys, reducing the need for multiple transactions and enabling seamless transfers between modes (Chowdhury and Ceder, 2016). The integration of feeder bus services and smart card systems in Delhi has yielded significant positive impacts on ridership and travel times. According to DMRC (2021), the average daily ridership of the Delhi Metro increased from 2.7 million in 2018 to 3.2 million in 2020, with a significant portion of this growth attributed to the improved last-mile connectivity provided by the feeder buses. A study by Goel and Tiwari (2016) found that the integration of feeder services reduced the average access and egress time for metro users by 15 % and 20 %, respectively. Furthermore, the introduction of the "More Delhi" smart card led to a 12 % increase in the number of multimodal trips and a 5 % reduction in the average travel time for commuters using the integrated ticketing system (MoHUA, 2021). These quantitative assessments demonstrate the success of multimodal integration initiatives in Delhi, highlighting the potential for similar approaches to enhance ridership, reduce travel times, and improve overall urban mobility in other Indian cities.

6.2. Ahmedabad

Janmarg Bus Rapid Transit System Ahmedabad, the largest city in the state of Gujarat, has successfully implemented a Bus Rapid Transit (BRT) system called Janmarg, which has transformed the city's public transport landscape (Suzuki et al., 2013). Launched in 2009, the Janmarg BRT system features dedicated bus lanes, intelligent transportation systems, and modern bus stations with level boarding and real-time passenger information displays (Mahadevia et al., 2013).

The success of the Janmarg BRT system lies in its integration with other modes of transport, including the city bus service, auto-rickshaws, and non-motorized modes (Suzuki et al., 2013). The BRT stations are designed to facilitate seamless transfers between modes, with designated spaces for auto-rickshaw stands and bicycle parking (Mahadevia et al., 2013). Moreover, the introduction of a common mobility card, known as the "Janmitra" card, has enabled integrated ticketing across the BRT and city bus services (AMC, 2021).

The Janmarg BRT system has not only improved the efficiency and reliability of public transport in Ahmedabad but has also contributed to social inclusion and environmental sustainability (Mahadevia et al., 2013). The system has enhanced accessibility to jobs, education, and healthcare facilities for the city's residents, particularly those from low-income communities (Suzuki et al., 2013).

Fig. 5 illustrates the growth in daily ridership of the Delhi Metro and Ahmedabad BRT systems over the past decade. Both systems have witnessed a steady increase in ridership, indicating the growing acceptance and popularity of integrated public transport services among commuters.

To put the growth in daily ridership of the Delhi Metro and Ahmedabad BRT into perspective, it is useful to compare these figures with the overall travel demand increases in the respective cities. According to the Delhi Traffic Police (2021), the total number of vehicles registered in Delhi grew from 7.4 million in 2010 to 12.1 million in 2020, representing a 63 % increase over the decade. In comparison, the daily ridership of the Delhi Metro grew by 125 % during the same period, from 1.2 million in 2010 to 2.7 million in 2020 (DMRC, 2021). Similarly, in Ahmedabad, the total number of vehicles increased by 72 % between 2010 and 2020, from 2.1 million to 3.6 million (AMC, 2021). The daily ridership of the Ahmedabad BRT, however, grew by 220 % during this period, from 100,000 in 2010 to 320,000 in 2020 (AMC, 2021). These comparisons demonstrate that the growth in daily ridership of the Delhi Metro and Ahmedabad BRT outpaced the overall travel demand increases in the respective cities, highlighting the substantial impact of these multimodal integration initiatives in attracting users to public transport.

7. International best practices in multimodal integration

To provide a benchmarking perspective for advancing multimodal integration in India, it is instructive to examine the best practices from cities globally known for their successful integrated transport systems. London, Paris, and Tokyo are often cited as exemplars of multimodal integration, characterized by seamless connectivity, integrated ticketing, and user-friendly information systems (Garau et al., 2024). These cities have achieved high levels of public transport ridership and reduced car dependence through a combination of infrastructure investments, land-use planning, and demand management measures. It is instructive to examine the best practices from countries facing similar challenges, such as China and Brazil. In China, cities like Guangzhou and Zhengzhou have successfully implemented bus rapid transit (BRT) systems integrated with metro rail, bicycling, and walking infrastructure, resulting in increased public transport ridership, reduced travel times, and improved air quality (Jiang et al., 2021). China's focus on transit-oriented development (TOD) and the integration of land-use planning with transportation, as exemplified by the Shenzhen Metro system, offers valuable lessons for Indian cities (Chen et al., 2019). In Brazil, São Paulo's "Bilhete Único" (Single Ticket) system has facilitated seamless transfers between bus, metro, and commuter rail services, leading to increased public transport use and reduced travel costs for commuters (Andrade et al., 2023). While the specific contexts and challenges may differ, the experiences of China and Brazil offer valuable strategies and lessons that can inform India's approach to multimodal integration and sustainable urban mobility.

Another notable example of successful multimodal integration is the Dutch and Danish approach to integrating cycling and public transport. Cities like Amsterdam and Copenhagen have developed extensive networks of cycling infrastructure, including dedicated bike lanes, parking facilities, and bike-sharing systems, which are closely integrated with public transport nodes (Buehler and Pucher, 2011). This integration has resulted in high levels of cycling and public transport use, contributing to reduced congestion, improved air quality, and enhanced public health outcomes. The experiences of these global cities offer valuable lessons for Indian policymakers and planners seeking to advance multimodal integration. While the specific contexts and challenges may differ, the core principles of integrated planning, user-centric design, and sustainable travel incentives remain relevant and applicable. By adapting and localizing these best practices, Indian cities can develop contextually appropriate strategies for achieving sustainable and inclusive urban mobility.

8. Recommendations for advancing multimodal integration in India

Based on the analysis of the current state of urban mobility, opportunities, challenges, and successful case studies, this section presents recommendations for advancing multimodal integration in Indian cities.

8.1. Policy and regulatory reforms

To create an enabling environment for multimodal integration, it is essential to introduce policy and regulatory reforms that promote coordination and collaboration among various stakeholders. The government should develop a comprehensive national policy framework for multimodal integration, setting clear guidelines and standards for the planning, design, and implementation of integrated transport systems (Tanwar and Agarwal, 2024). Additionally, the establishment of a unified metropolitan transport authority (UMTA) in each city can help streamline decision-making processes and ensure the effective coordination of different transport modes and agencies (Sharma and Newman, 2017).

8.2. Infrastructure development and investment

Investing in the development of integrated transport infrastructure is crucial for the successful implementation of multimodal integration. This includes the construction of intermodal terminals, the improvement of pedestrian and cycling infrastructure, and the upgrading of public transport systems (Mahadevia et al., 2013). The government should allocate adequate financial resources for these projects and explore innovative funding mechanisms, such as value capture financing and public-private partnerships (Sharma and Newman, 2017). Moreover, the investment in intelligent transportation systems (ITS) and integrated ticketing solutions can greatly enhance the efficiency and user experience of multimodal journeys (Tanwar and Agarwal, 2024).

8.3. Capacity building and stakeholder engagement

Advancing multimodal integration in India requires a concerted effort towards capacity building and stakeholder engagement. The government should invest in training and skill development programs for urban transport professionals, equipping them with the necessary knowledge and expertise to plan and implement integrated transport systems (Tanwar and Agarwal, 2024). Furthermore, engaging with stakeholders, including transport operators, user groups, and the general public, is essential to foster a sense of ownership and encourage behavioral change (Jain et al., 2018). Public awareness campaigns and participatory planning processes can help build support for multimodal integration initiatives and ensure their long-term success (Chowdhury and Ceder, 2016). Fig. 6 presents an interactive Sankey diagram illustrating the recommendations for advancing multimodal integration in India. The diagram showcases the flow and interconnectedness of the three main categories: policy and regulatory reforms, infrastructure development and investment, and capacity building and stakeholder engagement. Within each category, the key strategies and actions are highlighted, such as the development of a comprehensive national policy framework, the establishment of unified metropolitan transport authorities (UMTAs), the construction of intermodal terminals, the improvement of pedestrian and cycling infrastructure, and the implementation of training and skill development programs (Mahadevia et al., 2013; Sharma and Newman, 2017).

The Sankey diagram effectively visualizes the relationships and relative importance of each recommendation, emphasizing the need for a holistic and coordinated approach to advance multimodal integration in Indian cities. By interacting with the diagram, users can explore the specific recommendations and their connections, gaining a deeper understanding of the strategies required to create sustainable, efficient, and inclusive urban transport systems.

Develop a comprehensive network of pedestrian and cycling infrastructure, including dedicated lanes, signage, and crossing facilities, to promote active travel and enhance last-mile connectivity to public transport nodes (Hernández et al., 2023).

8.4. Context-specific policy recommendations

To effectively advance multimodal integration in India, it is crucial to tailor policy recommendations to the specific contexts of different city scales. Mega-cities and medium-sized cities face distinct challenges and opportunities due to their varying characteristics, such as population size, urban form, resource availability, and institutional capacities. By understanding these differences and adapting strategies accordingly, policymakers can develop targeted interventions that address the unique needs of each city scale.

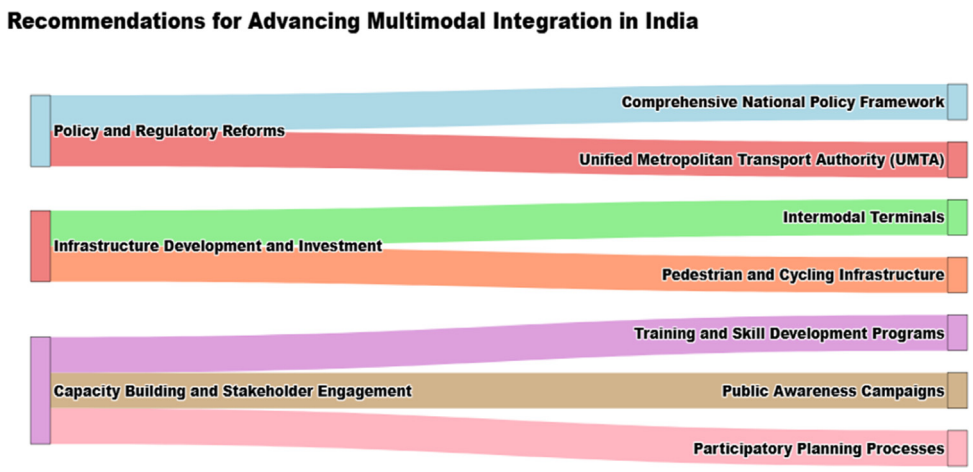

Fig. 6. Sankey diagram of recommendations for advancing multimodal integration in India.

Mega-cities, such as Delhi, Mumbai, and Kolkata, are characterized by their large population, high density, and complex urban systems. These cities often have extensive public transport networks, including metro rail and bus rapid transit (BRT) systems, which form the backbone of their urban mobility. However, mega-cities also face significant challenges, such as severe congestion, air pollution, and social inequity, due to the sheer scale of their transportation demand and the limitations of their existing infrastructure.

In the context of multimodal integration, mega-cities should prioritize the following policy recommendations:

1. Establish an integrated transport authority: Create a unified body responsible for coordinating planning, development, and operations across different modes of transport, ensuring seamless integration and efficient resource allocation (Vyas et al., 2024). In mega-cities like Delhi and Mumbai, where multiple agencies manage different aspects of the transport system, an integrated authority can help overcome institutional fragmentation and improve coordination. The authority should have a clear mandate, adequate resources, and decision-making powers to effectively implement multimodal integration strategies (Tanwar and Agarwal, 2024).
2. Prioritize high-capacity public transport: Invest in the expansion and improvement of metro rail, suburban rail, and bus rapid transit (BRT) systems to cater to the high travel demand and reduce dependence on private vehicles (Kathuria et al., 2016). Mega-cities should focus on developing a dense network of high-capacity public transport corridors, integrating them with feeder services, and ensuring last-mile connectivity (Sharma and Newman, 2017). This approach aligns with the concept of transit-oriented development (TOD), which emphasizes compact, mixed-use development around public transport nodes (Suzuki et al., 2013).
3. Implement congestion pricing and parking management: Introduce congestion charges in high-density areas and develop a comprehensive parking policy to discourage private vehicle usage and promote a shift towards public transport (Marazi et al., 2022). Mega-cities can learn from successful examples like Singapore's Electronic Road Pricing (ERP) system and London's Congestion Charge, which have effectively reduced traffic congestion and encouraged the use of public transport (Chowdhury et al., 2018). These measures should be accompanied by the provision of affordable and convenient public transport alternatives to ensure equitable access (Mahadevia et al., 2013).
4. Enhance first- and last-mile connectivity: Provide feeder services, such as minibuses, shared auto-rickshaws, and bicycle-sharing systems, to improve access to public transport nodes and encourage multimodal trips (Rangwala et al., 2018). Mega-cities should leverage technology-based solutions, such as demand-responsive transport (DRT) and mobility-as-a-service (MaaS) platforms, to optimize feeder services and improve connectivity in peripheral areas (Jittrapirom et al., 2017). These interventions can help bridge the gap between high-capacity public transport and the diverse mobility needs of users (Kumar et al., 2019).
5. Leverage technology for integrated ticketing and passenger information: Develop a unified ticketing system across different modes and provide real-time passenger information through mobile apps and digital displays to enhance convenience and reliability (Gupta et al., 2024). Mega-cities should invest in smart card systems, like the Octopus card in Hong Kong or the Oyster card in London, which enable seamless transfers across modes and facilitate integrated fare collection (Chowdhury and Ceder, 2016). Real-time passenger information systems, such as those deployed in Seoul and Singapore, can help users make informed decisions and optimize their multimodal journeys (Tanwar and Agarwal, 2024).

On the other hand, medium-sized cities, such as Bhopal, Indore, and Surat, have different characteristics and challenges compared to mega-cities. These cities have a smaller population and lower density, but they are experiencing rapid growth and urbanization. Medium-sized cities often have limited public transport infrastructure and rely more on private vehicles and intermediate public transport (IPT) modes, such as auto-rickshaws and shared taxis.

To advance multimodal integration in medium-sized cities, policymakers should focus on the following recommendations:

1. Develop a comprehensive mobility plan: Prepare a long-term, integrated mobility plan that prioritizes sustainable modes, such as public transport, walking, and cycling, and identifies key projects and funding sources (Shaban et al., 2020). Medium-sized cities should adopt a participatory planning approach, involving stakeholders from different sectors and the community, to ensure that the plan reflects local needs and aspirations (Jain et al., 2018). The mobility plan should be aligned with the city's land-use and development goals, promoting compact, transit-oriented growth (Sharma and Newman, 2017).
2. Improve bus services: Modernize the bus fleet, optimize routes, and implement intelligent transport systems (ITS) to enhance the efficiency, reliability, and attractiveness of bus services (Liu and Miller, 2020). Medium-sized cities should focus on developing a hierarchical bus network, with high-frequency services on major corridors and feeder routes in residential areas (Verma et al., 2019). The use of ITS technologies, such as automatic vehicle location (AVL) and real-time passenger information systems, can improve operational efficiency and user satisfaction (Vyas et al., 2024).
3. Create dedicated infrastructure for non-motorized transport: Develop a network of safe and comfortable pedestrian and cycling infrastructure, including sidewalks, crossings, and bicycle lanes, to promote active mobility and improve accessibility (Vijay et al., 2024). Medium-sized cities should adopt a complete streets approach, which prioritizes the needs of pedestrians, cyclists, and public transport users in street design and allocation of road space (Rahul and Verma, 2018). The provision of shade, lighting, and amenities along walking and cycling routes can further encourage the use of non-motorized modes (Jain et al., 2018).
4. Integrate land-use and transport planning: Encourage mixed-use development and transit-oriented development (TOD) around major public transport nodes to reduce travel distances and promote sustainable travel behavior (Jain and Singh, 2019). Medium-sized cities should revise their land-use regulations and building codes to incentivize compact, mixed-use development and discourage sprawl (Sharma and Newman, 2017). The integration of land-use and transport planning can help create self-contained neighborhoods, where daily needs can be met within walking or cycling distance (Suzuki et al., 2013).
5. Foster public-private partnerships: Collaborate with the private sector to finance and operate multimodal integration initiatives, such as intermodal terminals, integrated ticketing systems, and data-sharing platforms (Shukla and Sharma, 2018). Medium-sized cities can leverage the expertise and resources of private partners to develop innovative solutions and improve service quality (Kumar et al., 2019). Public-private partnerships (PPPs) can help overcome financial constraints and accelerate the implementation of multimodal integration projects (Sharma and Newman, 2017).

To implement these recommendations, policymakers can follow a step-by-step strategy:
Step 1: Assess the current state of urban mobility and identify key challenges and opportunities specific to the city.

- Conduct a comprehensive assessment of the city's transport infrastructure, travel patterns, and user needs (Tanwar and Agarwal, 2024).
- Identify the main challenges, such as congestion, air pollution, road safety, and accessibility, using data-driven analysis and stakeholder consultation (Verma et al., 2021).
- Evaluate the potential opportunities for multimodal integration, considering the city's existing assets, planned developments, and best practices from similar contexts (Sharma and Newman, 2017).

Step 2: Develop a vision and goals for multimodal integration, aligned with the city's overall sustainable development objectives.

- Formulate a clear and compelling vision for the city's future mobility system, emphasizing integration, sustainability, and inclusivity (Jain et al., 2018).
- Set specific, measurable, achievable, relevant, and time-bound (SMART) goals for multimodal integration, such as modal split targets, accessibility indices, and emissions reduction (Mahadevia et al., 2013).
- Align the vision and goals with the city's broader development agenda, such as economic growth, social equity, and environmental sustainability (Suzuki et al., 2013).

Step 3: Engage stakeholders, including transport operators, user groups, and local communities, to build consensus and support for the proposed interventions.

- Identify and map the key stakeholders, their interests, and their influence on the multimodal integration process (Kumar et al., 2019).
- Conduct participatory workshops, focus group discussions, and public consultations to gather stakeholder inputs and feedback on the proposed interventions (Jain et al., 2018).
- Build consensus among stakeholders through transparent communication, negotiation, and conflict resolution (Shukla and Sharma, 2018).

Step 4: Prepare a detailed action plan, outlining the specific projects, timelines, and funding sources for each recommendation.

- Prioritize the recommended interventions based on their feasibility, impact, and alignment with the city's vision and goals (Tanwar and Agarwal, 2024).
- Develop a phased implementation plan, specifying the short-term, medium-term, and long-term actions, along with their expected outcomes and resource requirements (Sharma and Newman, 2017).
- Identify the funding sources, such as government budgets, user charges, value capture mechanisms, and private investments, for each project (Shukla and Sharma, 2018).

Step 5: Establish a monitoring and evaluation framework to track progress, assess impacts, and make necessary adjustments.

Table 1
Multimodal integration challenges, priorities, and recommended strategies for mega-cities and medium-sized cities in India.

City type	Key challenges	Priorities	Recommended strategies
Mega-Cities	High travel demand and congestion	Development of high-capacity public transport	1. Establish an integrated transport authority
	Fragmented institutional framework	Seamless integration across modes	2. Prioritize high-capacity public transport
	Limited land availability	Demand management	3. Implement congestion pricing and parking management
			4. Enhance first- and last-mile connectivity
			5. Leverage technology for integrated ticketing and passenger information
Medium-Sized Cities	Rapidly growing travel demand	Improvement of bus services	6. Develop a comprehensive mobility plan
	Limited financial resources	Promotion of non-motorized transport	7. Improve bus services
	Inadequate public transport services	Transit-oriented development	8. Create dedicated infrastructure for non-motorized transport
			9. Integrate land-use and transport planning
			10. Foster public-private partnerships

- Define key performance indicators (KPIs) for each recommendation, aligned with the city's multimodal integration goals (Mahadevia et al., 2013).
- Set up a data collection and management system to regularly monitor the KPIs and evaluate the impacts of the interventions (Vyas et al., 2024).
- Use the monitoring and evaluation results to identify gaps, make course corrections, and update the action plan as needed (Kumar et al., 2019).

By tailoring policy recommendations to the specific contexts of mega-cities and medium-sized cities, policymakers can develop targeted strategies that address the distinct challenges and leverage the unique opportunities of each city scale. This context-specific approach is essential for achieving sustainable, efficient, and inclusive urban mobility through multimodal integration in India. Table 1 summarizes the key differences between mega-cities and medium-sized cities in terms of their multimodal integration challenges, priorities, and recommended strategies.

This contextualization helps policymakers and practitioners understand the distinct needs and opportunities in each type of city and adopt a targeted approach to advance sustainable urban mobility.

9. Conclusion

9.1. Summary of findings

This investigation has explored the opportunities and challenges associated with advancing multimodal integration for sustainable urban mobility in India. The analysis of the current state of urban mobility in Indian cities has revealed a growing need for sustainable transport solutions to address the challenges of congestion, air pollution, and social inequity (Pucher et al., 2005; Tiwari, 2018). Multimodal integration, which involves the seamless integration of different transportation modes, has emerged as a promising approach to achieve sustainable urban mobility (Chowdhury et al., 2018). The study has identified several opportunities for multimodal integration in India, including supportive policy initiatives, technological advancements, and the potential for public-private partnerships (Tanwar and Agarwal, 2024; Sharma and Newman, 2017). However, the implementation of multimodal integration also faces significant challenges, such as institutional and regulatory barriers, financial constraints, and the need for behavioral change (Jain et al., 2018; Mahadevia et al., 2013). The case studies of successful multimodal integration initiatives in Delhi and Ahmedabad have demonstrated the potential benefits of integrated transport systems, including improved accessibility, reduced congestion, and enhanced social inclusion (Goel and Tiwari, 2016; Suzuki et al., 2013). Drawing from these experiences, the study has proposed a set of recommendations for advancing multimodal integration in Indian cities, focusing on policy and regulatory reforms, infrastructure development, capacity building, and stakeholder engagement (Tanwar and Agarwal, 2024; Sharma and Newman, 2017).

The case studies of the Delhi Metro and Ahmedabad BRT have demonstrated the potential benefits of integrated transport systems in reducing traffic congestion. In Delhi, the introduction of the metro system led to a 14 % increase in average travel speed on major roads and a 12 % decrease in the number of vehicles entering the city center between 2004 and 2014 (Goel and Tiwari, 2016). Similarly, the Ahmedabad BRT system contributed to a 25 % increase in average travel speed on its corridors during peak hours and a 15 % reduction in the volume of private vehicles along the corridors (Mahadevia et al., 2013). These findings provide compelling evidence of the effectiveness of multimodal integration in alleviating traffic congestion in Indian cities.

9.2. Future research directions

While this study has provided valuable insights into the opportunities and challenges of multimodal integration in India, there are several areas that require further research:

1. Evaluation of the long-term impacts of multimodal integration initiatives on sustainable urban mobility indicators, such as modal shift, emissions reduction, and social equity (Chowdhury and Ceder, 2016; Mishra et al., 2012).
2. Exploration of innovative funding mechanisms and business models for financing multimodal integration projects, including value capture financing and public-private partnerships (Sharma and Newman, 2017).
3. Investigation of the role of emerging technologies, such as autonomous vehicles, shared mobility services, and mobility-as-a-service (MaaS) platforms, in facilitating multimodal integration (Jittrapirom et al., 2017).
4. Comparative analysis of multimodal integration policies and practices across different Indian cities to identify best practices and lessons learned (Tanwar and Agarwal, 2024; Mahadevia et al., 2013).
5. Examination of the social and behavioral aspects of multimodal integration, including user preferences, acceptance, and the factors influencing travel behavior change (Jain et al., 2018; Verma et al., 2019).

By addressing these research gaps, future studies can contribute to a more comprehensive understanding of the potential and challenges of multimodal integration in the Indian context, and inform the development of effective policies and strategies for sustainable urban mobility. Furthermore, future research could explore the potential of recent technological advancements, such as real-time data integration, mobile apps, and IoT, in enhancing data analysis for multimodal integration. These technologies offer promising opportunities for collecting, processing, and visualizing large-scale, high-resolution data on travel behavior, network performance, and user preferences, facilitating evidence-based decision-making and responsive transport planning (Allam and Dhunny, 2019). Investigating the application of these technologies in the Indian context and addressing the associated challenges related to data privacy, security, and governance could provide valuable insights for advancing multimodal integration in the country.

Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declaration of competing interest

The authors declare that they have no conflict of interest.

CRediT authorship contribution statement

Rahul Tanwar: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Pradeep Kumar Agarwal:** Writing – review & editing, Supervision.

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References

Ahmedabad Municipal Corporation [AMC]. (2021). Janmarg - Ahmedabad Bus Rapid Transit System. https://ahmedabadcity.gov.in/portal/jsp/Static_pages/janmarg.jsp.
Allam, Z., Dhunny, Z.A., 2019. On big data, artificial intelligence and smart cities. Cities 89, 80–91. doi:10.1016/j.cities.2019.01.032.
Andrade, N.F., de Lima Junior, F.B., Soliani, R.D., de Souza Oliveira, P.R., de Oliveira, D.A., Siqueira, R.M., Macêdo, J., 2023. Urban Mobility: a review of challenges and innovations for sustainable transportation in Brazil. Revista de Gestão Social e Ambiental 17 (3). doi:10.24857/rgsa.v17n3-009, e03303-e03303.
Banister, D., 2008. The sustainable mobility paradigm. Transp. Policy (Oxf) 15 (2), 73–80. doi:10.1016/j.tranpol.2007.10.005.
Buehler, R., Pucher, J., 2011. Sustainable transport in Freiburg: lessons from Germany's environmental capital. Int. J. Sustain. Trans. 5 (1), 43–70. doi:10.1080/15568311003650531.
Chen, Z., Du, H., Li, J., Southworth, F., Ma, S., 2019. Achieving low-carbon urban passenger transport in China: insights from the heterogeneous rebound effect. Energy Economics 81, 1029–1041. https://ideas.repec.org/a/eee/eneeco/v81y2019icp1029-1041.html#:~:text=10.1016/j.eneco.2019.06.009.
Chowdhury, S., Ceder, A., 2016. Users' willingness to ride an integrated public-transport service: a literature review. Transp. Policy (Oxf) 48, 183–195. doi:10.1016/j.tranpol.2016.03.007.
Chowdhury, S., Ceder, A., Schwalger, B., 2018. The effects of travel time and cost savings on commuters' decision to travel on public transport routes involving transfers. J. Transp. Geogr. 68, 43–52. doi:10.1016/j.jtrangeo.2018.02.004.
Delhi Metro Rail Corporation [DMRC]. (2021). About us - Delhi Metro Rail Corporation. https://www.delhimetrorail.com/about_us.aspx.
Garau, C., Desogus, G., Torrisi, V., 2024. From smart urbanism to sustainable Urban mobility plan: a critical evaluation of the case of Cagliari. Smart Cities Energy Climate: Govern. Cities Low-Carbon Future 195–213. doi:10.1002/9781118641156.ch11.
Gijre, V., Gupta, S., 2020. Urban transport governance practice and challenges in an emerging economy–Case study of India. Transp. Res. Procedia 48, 2435–2445.
Goel, R., Tiwari, G., 2016. Access–egress and other travel characteristics of metro users in Delhi and its satellite cities. IATSS Res. 39 (2), 164–172. doi:10.1016/j.iatssr.2015.10.001.
Gupta, J., Khobragade, V.J., Upadhyay, R.K., 2024. Enhancing multimodal transportation in India: jogighopa Multimodal Logistics Park. In: Intelligent Transportation System and Advanced Technology. Springer Nature Singapore, Singapore, pp. 123–157.
Guttikunda, S.K., Mohan, D., 2014. *Re*-fueling road transport for better air quality in India. Energy Policy 68, 556–561. doi:10.1016/j.enpol.2013.12.067.

Hernández, J.R.E., Moghadam, S.T., Sharifi, A., Lombardi, P., 2023. Cities in the times of COVID-19: trends, impacts, and challenges for urban sustainability and resilience. J Clean Prod, 139735.
Hrelja, R., Pettersson, F., Westerdahl, S., 2017. The qualities needed for a successful collaboration: a contribution to the conceptual understanding of collaboration for efficient public transport. Sustainability 9 (4), 542. doi:10.3390/su9040542.
Jain, D., Singh, E., 2019. Transit oriented development in India: a critical review of policy measures. Int. J. Recent Technol. Eng 7 (6), 745–751.
Jain, S., Aggarwal, P., Kumar, P., Singhal, S., Sharma, P., 2018. Identifying public preferences using multi-criteria decision making for assessing the shift of urban commuters from private to public transport: a case study of Delhi. Transp. Res. Part F: Traffic Psychol. Behav. 24, 60–70. doi:10.1016/j.trf.2014.03.007.
Jiang, Y., Gu, P., Chen, Y., He, D., Mao, Q., 2021. Influence of land use and street characteristics on car ownership and use: evidence from Jinan, China. Transp. Res. Part D: Transp. Environ. 92, 102734. doi:10.1016/j.trd.2021.102734.
Jittrapirom, P., Caiati, V., Feneri, A.M., Ebrahimigharehbaghi, S., González, M.J.A., Narayan, J., 2017. Mobility as a service: a critical review of definitions, assessments of schemes, and key challenges. Urban Plann. 2 (2), 13–25. doi:10.17645/up.v2i2.931.
Kathuria, A., Parida, M., Ravi Sekhar, C., Sharma, A., 2016. A review of bus rapid transit implementation in India. Cogent Eng. 3 (1), 1241168. doi:10.1080/23311916.2016.1241168.
Koszowski, C., Gerike, R., Hubrich, S., Götschi, T., Pohle, M., Wittwer, R., 2019. Active mobility: bringing together transport planning, urban planning, and public health. Towards user-centric Transp. Europe: Challenge. Solutions Collab. 149–171.
Krylatov, A., Raevskaya, A., Zakharov, V., 2021. Travel demand estimation in urban road networks as inverse traffic assignment problem. Transp. Telecomm. J. 22 (3), 287–300. doi:10.2478/ttj-2021-0022.
Kumar, P.P., Sekhar, C.R., Parida, M., 2019. Identification of neighborhood typology for potential transit-oriented development. Transp. Res. Part D: Transp. Environ. 78, 102186. doi:10.1016/j.trd.2019.11.015.
Liu, L., Miller, H.J., 2020. Does real-time transit information reduce waiting time? an empirical analysis. Transp. Res. Part A: Policy Pract. 141, 167–179. doi:10.1016/j.tra.2020.09.014.
Luk, J., Olszewski, P., 2003. Integrated public transport in Singapore and Hong Kong. Road Transp. Res. 12 (4), 41–51.
Mahadevia, D., Joshi, R., Datey, A., 2013. Accessibility and sustainability of bus rapid transit in India. UNEP Risø Centre Energy Clim. Sustain. Dev.. https://www.uncclearn.org/wp-content/uploads/library/unep24.pdf.
Marazi, N.F., Majumdar, B.B., Sahu, P.K., Potoglou, D., 2022. Congestion pricing acceptability among commuters: an Indian perspective. Res. Transp. Econ. 95, 101180.
Martens, K., 2017. Transport justice: Designing fair Transportation Systems. Routledge doi:10.4324/9781315746852.
Ministry of Housing and Urban Affairs [MoHUA]. (2015). Smart Cities mission. Government of India. http://smartcities.gov.in/.
Ministry of Housing and Urban Affairs [MoHUA]. (2017). Green Urban Mobility Scheme. Government of India. http://mohua.gov.in/cms/green-urban-mobility-scheme.php.
Ministry of Housing and Urban Affairs [MoHUA]. (2021). Urban transport in Indian cities: a comprehensive study. Government of India. https://mohua.gov.in/urban-transport-study.php.
Ministry of Road Transport and Highways [MoRTH]. (2019). Road Transport Year Book (2017-18 & 2018-19). Government of India. https://morth.nic.in/road-transport-year-book-2017-18-2018-19.
Ministry of Urban Development [MoUD]. (2006). National Urban transport policy. Government of India. http://mohua.gov.in/upload/uploadfiles/files/TransportPolicy(2).pdf.
Mishra, S., Welch, T.F., Jha, M.K., 2012. Performance indicators for public transit connectivity in multi-modal transportation networks. Transp. Res. Part A: Policy Pract. 46 (7), 1066–1085. doi:10.1016/j.tra.2012.04.006.
Mohan, D., Tiwari, G., Mukherjee, S., 2017. City-level analysis of road traffic fatalities in India. Int. J. Inj. Contr. Saf. Promot. 24 (1), 83–92. doi:10.1080/17457300.2015.1128004.
Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Ann. Intern. Med. 151 (4), 264–269. doi:10.7326/0003-4819-151-4-200908180-00135.
NITI Aayog & Rocky Mountain Institute [RMI]. (2021). Mobilising electric vehicle financing in India. https://rmi.org/insight/mobilizing-ev-finance-in-india/.
Oeschger, G., Carroll, P., Caulfield, B., 2020. Micromobility and public transport integration: the current state of knowledge. Transp. Res. Part D: Transp. Environ. 89, 102603. doi:10.1016/j.trd.2020.102628.
Poorjafari, V., Yue, W.L., 2014. Integration of public transport systems using transfer coordination approach. J. Eastern Asia Soc. Transp. Stud. 10, 826–841. doi:10.11175/easts.10.826.
Pucher, J., Buehler, R., 2017. Cycling towards a more sustainable transport future. Transp. Rev. 37 (6), 689–694. doi:10.1080/01441647.2017.1340234.
Pucher, J., Korattyswaropam, N., Mittal, N., Ittyerah, N., 2005. Urban transport crisis in India. Transp. Policy (Oxf) 12 (3), 185–198. doi:10.1016/j.tranpol.2005.02.008.
Rahul, T.M., Verma, A., 2018. Sustainability analysis of pedestrian and cycling infrastructure - a case study for Bangalore. Case Stud. Transp. Policy 6 (4), 483–493. doi:10.1016/j.cstp.2018.06.001.
Rangwala, L., Mathews, R., Sridhar, S., 2018. Shifting discourse about transit-oriented development in Mumbai, India. Transp. Res. Record 2672 (8), 875–885. doi:10.3141/2451-07.
Rawal, T., Devadas, V., & Numar, N. (2014). Integrated multimodal transportation in India. In changing spectrum of Human settlements and planning education, At Guru Ramdas school of planning, GNDU, Amritsar, conference paper.
Rosas-Satizábal, D., Rodriguez-Valencia, A., 2019. Factors and policies explaining the emergence of the bicycle commuter in Bogotá. Case Stud. Transp. Policy 7 (1), 138–149. doi:10.1016/j.cstp.2018.12.007.
Scheepers, E., Wendel-Vos, W., den Broeder, L., van Kempen, E., van Wesemael, P.J.V., Schuit, A.J., 2016. Shifting from car to active transport: a systematic review of the effectiveness of interventions. Transp. Res. Part A: Policy Pract. 86, 163–180. doi:10.1016/j.tra.2014.10.015.
Shaban, A., Kourtit, K., Nijkamp, P., 2020. India's urban system: sustainability and imbalanced growth of cities. Sustainability, 12 (7), 2941.
Shaheen, S., Bouzaghrane, M.A., 2021. Mobility and energy impacts of shared automated vehicles: a review of recent literature. Curr. Sustain./Renew. Energy Rep. 8 (2), 79–86. https://link.springer.com/article/10.1007/s40518-019-00135-2.
Sharma, N., Newman, P., 2017. Urban rail and sustainable development: key lessons from Hong Kong, New York, London and India for emerging cities. Transp. Res. Proc. 26, 92–105. doi:10.1016/j.trpro.2017.07.011.
Shukla, A., Sharma, N., 2018. A study of public-private partnerships for sustainable urban mobility in Indian cities. J. Infrastruct. Dev. 10 (1–2), 41–57. doi:10.1177/0974930618811209.
Stone, M., Aravopoulou, E., 2018. Improving journeys by opening data: the case of transport for London (TfL). Bottom Line 31 (1), 2–15. doi:10.1108/BL-12-2017-0035.
Suzuki, H., Cervero, R., Iuchi, K., 2013. Transforming Cities With transit: Transit and Land-Use Integration For Sustainable Urban Development. The World Bank doi:10.1596/978-0-8213-9745-9.
Tanwar, Rahul, Agarwal, Pradeep Kumar, 2024. Assessing travel time performance of multimodal transportation systems using fuzzy-analytic hierarchy process: a case study of Bhopal City. Heliyon 10 (17).
Tanwar, R., Agarwal, P.K., 2025a. Investigating the factors determining service quality in Bhopal's multimodal public transport system: a factor analysis. Case Stud. Transp. Pol. 19, 101317.
Tanwar, R., Agarwal, P.K., 2025b. Measuring accessibility for multimodal public transport system using multinomial logit model. KSCE J. Civil Eng. 100193.
Tanwar, Rahul, Kumar Agarwal, Pradeep, 2024. Analysis of the determinants of service quality in the multimodal public transport system of Bhopal city using structural equation modelling (SEM) and factor analysis. Expert Syst. Appl. 256 (2024), 124931. doi:10.1016/j.eswa.2024.124931, ISSN 0957-4174.
Tiwari, G., 2018. Urban transport in Indian cities. Econ. Polit. Wkly 53 (47), 57–65. https://www.epw.in/journal/2018/47/special-articles/urban-transport-indian-cities.html.
UN DESA. (2018). World urbanization prospects: the 2018 revision. United Nations Department of Economic and Social Affairs, Population Division. https://population.un.org/wup/.

Verma, A., Kumari, A., Tahlyan, D., Hosapujari, A.B., 2019. Development of hub and spoke model for improving operational efficiency of bus transit system in Delhi. Case Stud. Transp. Policy 7 (3), 516–525. doi:10.1016/j.cstp.2019.05.003.

Verma, A., Harsha, V., Subramanian, G.H., 2021. Evolution of urban transportation policies in India: a review and analysis. Transp. Dev. Econ. 7 (2), 25. doi:10.1007/2Fs40890-021-00136-1.

Vijay, N.C., Rokade, S., Bivina, G.R., 2024. Towards safer streets: a review of child pedestrian behavior and safety worldwide. Transp. Res. Part F: Traffic Psychol. Behav. 103, 638–660. doi:10.1016/j.trf.2024.05.005.

Vyas, A.R., Patel, P.J., 2024. A review of public road transport in India: challenges, innovations and policy recommendations. Grenze Int. J. Eng. Technol. (GIJET) 10.