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Evaluating public bicycle sharing system in Ahmedabad, Gujarat: A multi-criteria decision-making approach[☆]

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ABSTRACT

This study evaluates the existing Public Bicycle Sharing System (PBSS) at Ahmedabad, Gujarat by applying four decision-making methods such as Analytic Hierarchy Process (AHP), Fuzzy AHP, Analytic Network Process (ANP), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The study aims to identify the most effective strategies for improving PBSS, focusing on safety, infrastructure, user convenience, and environmental impact. The analysis shows that Enhanced Non-Motorized Transport (NMT) Infrastructure and Expansion of Bicycle Networks are the preferred alternatives across all methods. Personal safety and safe cycling infrastructure are identified as critical factors influencing the success of PBSS. Socio-demographic data reveals a male-dominant user base, with financial barriers and safety concerns limiting broader adoption. Positive perceptions of cycle design are noted, though electric and hybrid cycles are preferred due to climatic conditions. Monthly variations in ridership demonstrate significant fluctuations, peaking at 68,529 rides in March, underscoring the need for targeted interventions during peak periods. The study provides a robust framework for transport planners, emphasizing safety, inclusivity, and affordability. Future research should focus on expanding electric cycle options and enhancing gender inclusivity in PBSS.

1. Introduction

Cycling has emerged as a sustainable, healthy, and cost-effective mode of transportation, gaining further prominence during the pandemic when motorized vehicles were less utilized. As cities strive to create more inclusive and sustainable transport environments, shifting from private vehicles to public transport becomes increasingly crucial. Public Bicycle Sharing Systems (PBSS) play a significant role in this transition, especially in metro cities where they are actively implemented. PBSS are flexible transportation services that allow users to rent bicycles for short distances [1,2]. These systems typically offer a range of bicycles, including pedal, geared, electric, and pedal-assist models, to cater to various needs and preferences. Rental options include hourly, daily, weekly, monthly, and annual subscriptions, with discounts and long-term leases available. PBSS aims to improve cycling infrastructure and address end-mile connectivity issues associated with public transportation [3]. In metropolitan areas, PBSS plays a vital role in enhancing urban mobility. It provides an economical and eco-friendly alternative

to motorized transport, contributing to reduced traffic congestion and lower emissions. By integrating these systems with existing public transportation networks, PBSS improves last-mile connectivity, making public transit more accessible and efficient.

Despite their benefits, PBSS faces several challenges. Transport agencies often view these systems as competitors to their core services, which can hinder their adoption and growth. Furthermore, increased awareness and education are needed to bridge the gap between PBSS and traditional public transport modes. Ensuring that these systems are inclusive and cater to diverse demographic groups including different genders, ages and physical abilities, is essential for maximizing their impact [4]. The concept of Public Bicycle Sharing (PBS) was first introduced in India in 2010 with the launch of the Pune Cycle Plan. Since its inception, PBS has significantly evolved and expanded across various Indian cities, including Delhi, Chennai, Bengaluru, Ahmedabad, Jaipur, Udaipur, Mumbai, Kochi, and Nagpur. Initially designed to promote cycling for recreational purposes, the service has grown to serve as a viable option for daily commutes as well. As urban planners

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and government authorities have increasingly focused on sustainable and green mobility solutions, PBS has gained prominence as a tool for reducing traffic congestion and pollution. The system's role in promoting eco-friendly transport aligns with broader goals of enhancing urban sustainability.

One of the major advancements in PBS in India is the integration of technology. The introduction of mobile applications and GPS-Bluetooth-enabled bicycles has streamlined the user experience, making it more convenient and accessible [5]. In cities like Delhi and Bangalore, smart card systems have been implemented, facilitating cashless transactions and ensuring a smoother service experience for users. Another significant development is the integration of PBS with other transportation modes, such as metro rail and public buses. This integration has improved last-mile connectivity, allowing users to seamlessly transition between different modes of transport. It has also increased the utilization of bicycles for short commutes, further promoting the use of sustainable transport options. Despite these advancements, the growth of PBS in India has encountered several challenges. Issues such as inadequate infrastructure, lack of public awareness and education, safety concerns, and vandalism have impeded the system's effectiveness and sustainability. Addressing these challenges is crucial for the continued success and expansion of PBS in India [6].

MYBYK, a Public Bike Sharing System, commenced its operations in Ahmedabad from 2014. Over the years, MYBYK has expanded its presence to several major Indian cities, including Indore, Kochi, Mumbai, Udaipur, Nagpur, and Mysuru. The service provides an accessible option for renting bicycles for short distances, fostering eco-friendly transportation and encouraging healthier lifestyles among users. MYBYK has earned significant recognition for its contributions to sustainable urban mobility. Notably, it received the Stylish Sustainable Civic Mobility Award at the Urban Mobility India Conference in 2017. Additionally, in 2019, MYBYK was selected for the Shell Foundation's accelerator program, which supports promising startups focused on sustainable development. The company has forged strategic partnerships to enhance its visibility and reach. For example, it has collaborated with Indian Railways to offer bicycles for use at train stations, facilitating smoother transitions between rail and bike transport. MYBYK has also partnered with retail outlets, such as Decathlon, to promote bicycle use for both personal and commercial purposes. As of now, MYBYK operates extensively in Ahmedabad, where it has established 253 stations and maintains a fleet of 6000 bicycles. The service records an impressive average of 50,000 rides per month and has 1200 subscribers who benefit from the flexibility to take bicycles home and return or exchange them during their subscription period. MYBYK's operational footprint extends across six Indian cities—Ahmedabad, Indore, Mumbai, Udaipur, Nagpur, and Kochi—boasting over 10,000 bicycles and >>500 PBS stations. With a user base of 750,000, the service has demonstrated substantial growth and acceptance. The company is poised to enter Mysuru in June 2023, further broadening its reach. MYBYK has modernized its operations by integrating Internet of Things (IoT) technology and pedal-assist bicycles, enhancing the overall user experience. The company's innovative approach includes updating the traditional Trin-Trin model to better suit contemporary needs.

Looking ahead, PBS service is anticipated to expand to Bengaluru by the end of 2023, with operations along the city's metro lines. This development will further contribute to the growing network of sustainable transportation options in India. This study evaluates existing PBSS at Ahmedabad, Gujarat by applying four decision-making methods such as Analytic Hierarchy Process (AHP), Fuzzy AHP, Analytic Network Process (ANP), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The alternatives assessed include Enhanced Non-Motorized Transport (NMT) Infrastructure, Expansion of Bicycle Network, Implementation of Slow Streets, Awareness and Education Campaigns, and Integration with Public Transport. The study aims to identify effective parameters that influence the use of cycling in urban areas, with a focus on making sustainable transportation accessible to

all. By analyzing factors that affect the success of PBSS, the study seeks to provide insights into where and how these systems can be more effectively implemented. This includes understanding user preferences, system design, and policy implications. Despite the growing adoption of Public Bicycle Sharing Systems (PBSS) in Indian cities, their effectiveness remains constrained by fragmented infrastructure, safety concerns, and socio-demographic disparities in usage. There is a lack of comprehensive, data-driven frameworks that evaluate improvement strategies from multiple decision-making perspectives. Addressing this gap, the present study aims to systematically evaluate PBSS in Ahmedabad using robust multi-criteria decision-making (MCDM) approaches. To assess the most impactful strategies for enhancing PBSS, this study applies four distinct MCDM techniques: AHP, Fuzzy AHP, ANP, and TOPSIS. Each method captures a different decision-making nuance—from handling uncertainty (Fuzzy AHP) to modeling interdependencies and performance proximity. A structured survey of 1000 respondents, secondary data from MYBYK and expert inputs form the basis of the evaluation.

Across all four decision-making models, Enhanced Non-Motorized Transport (NMT) Infrastructure consistently emerged as the preferred alternative, followed by Expansion of the Bicycle Network. Personal safety and safe infrastructure at junctions were identified as the most critical criteria. The results also highlight the underrepresentation of women and higher-income groups in PBSS usage, emphasizing the need for inclusive planning. This study contributes a comparative and integrated framework for evaluating urban mobility interventions, especially PBSS strategies, using multiple MCDM methods. It offers practical recommendations for planners and policymakers to prioritize infrastructure, safety, and affordability. It also proposes directions for future research, including gender-responsive PBSS design and the integration of electric bicycles for climate resilience. By combining socio-demographic insights with rigorous decision-analysis techniques, the study presents a replicable model for evaluating PBSS in other Indian and global contexts.

2. Study about the public bicycle sharing systems

Public Bicycle Sharing Systems (PBSS) play a vital role in urban mobility and sustainability. Several factors, including technological advancements, safety, user satisfaction, infrastructure design, and policy support, contribute to the success of PBSS. These factors align with specific criteria that influence user preferences, system efficiency, and overall system sustainability. Below, the literature is organized into thematic clusters and linked to the relevant evaluation criteria.

2.1. Technological advancements and system efficiency

The integration of advanced technology is essential for enhancing the efficiency and user experience of Public Bicycle Sharing Systems (PBSS). Studies have highlighted the transformative role of smart technologies such as real-time data analytics, smart locks, and mobile applications in improving operational efficiency and user satisfaction. Munkácsy & Monzón (2017) and Bieliński & Wążna (2018) underscore the importance of these technologies in optimizing the availability of bikes, streamlining the rental process, and reducing operational costs. These innovations allow for better tracking of bikes, improve the user interface, and increase system reliability by offering features like user feedback, bike maintenance requests, and efficient bike deployment. Moreover, the advent of electric bikes and docking stations is expanding the scope and accessibility of PBSS, making them adaptable to different urban mobility needs [7,8]. Shaheen et al. (2013) argue that these technologies not only enhance operational performance but also ensure user convenience and satisfaction by offering a seamless and interactive experience [9]. Moreover, Teixeira et al. (2023) highlighted the importance of contactless payment systems and smart tracking, particularly considering the COVID-19 pandemic, as these systems address safety concerns and improve user confidence in the services [10].

Researchers have also discussed how data analytics and smart technologies were leveraged to optimize bike-sharing operations and respond to changing user demands. O'Mahony and Shmoys (2015) explored the application of real-time data analytics to predict user demand patterns, allowing for efficient redistribution of bikes and optimization of station capacities [11]. Similarly, Freund et al. (2019) focused on using machine learning algorithms to forecast bike availability and manage fleet resources dynamically, improving operational efficiency and ensuring user satisfaction by minimizing bike shortages and overages [12]. Technological innovations affect separate cycle lanes by ensuring real-time bike availability, reducing congestion on cycling paths. System efficiency is also improved as smart bikes and systems help in managing bike fleet distribution and predicting demand, ensuring fewer bikes are left stranded. The integration of technology can also improve Personal safety through GPS tracking, helping to monitor and ensure their security.

2.2. Health, safety, and crisis resilience

The COVID-19 pandemic presented unprecedented challenges for PBSS, especially in terms of user safety and system sustainability. During the pandemic, concerns about hygiene and social distancing led to a greater demand for contactless and hygienic bike-sharing options. Raza et al. (2018) found that increased cycling benefits public health by improving physical fitness and reducing air pollution, a message that became even more pronounced during the pandemic when users prioritized safety [13]. Julio and Monzón (2022) examined the long-term impacts of the pandemic on PBSS, stressing the need for proactive strategies to ensure their sustainability during future crises. These strategies include introducing flexible pricing, ensuring hygiene management, and integrating technological solutions to foster resilience. The ongoing adaptation of PBSS in response to external shocks has proven to be essential for maintaining user confidence and ensuring system longevity [14]. Murat and Cakici (2024) explored how the pandemic shifted preferences towards systems that allowed minimal contact, highlighting the importance of hygiene and safety measures in user satisfaction [15]. The importance of Personal safety during pandemics and crisis situations is critical. Hygiene and contactless systems are directly linked to ensuring user safety. Clean air to breathe is also promoted as cycling in cities reduces vehicular emissions and encourages active transportation, contributing to better air quality.

2.3. Infrastructure and urban design

The physical infrastructure and design of bike-sharing systems play a critical role in influencing the effectiveness and accessibility of these systems. Research consistently shows that well-maintained bikes, strategically located stations, and easy access points significantly enhance user satisfaction and system utilization. Macioszek et al. (2020) and Guo et al. (2017) emphasize that users tend to prefer systems with well-distributed bike stations and clear access points, as this reduces barriers to use and ensures the bikes are readily available where they are needed most. In addition to station placement, the integration of PBSS with broader urban infrastructure is crucial [16,17]. Bencekri et al. (2024) and Mix et al. (2022) argue that effective integration with public transport networks, pedestrian areas, and bike lanes encourages greater use by ensuring seamless transfers between different modes of transport [18,19]. Furthermore, Wang et al. (2023) found that urban design elements, such as bike lanes and pedestrian-friendly streets, can increase bike-sharing usage by making it safer and more convenient for users to access and use the system [20]. This infrastructure directly influences several criteria, including separate cycle lanes are essential for safe cycling, as users prefer dedicated lanes that minimize risks from mixed traffic. Marked accident-prone areas should be addressed by city planners to ensure the safety of cyclists. Well-maintained bike lanes and clear traffic management can reduce the risk of accidents. Less traffic

improves cycling safety and the attractiveness of bike-sharing systems, as lower traffic volumes reduce the likelihood of collisions. Proper urban infrastructure ensures reduced vehicle speed, which directly contributes to cycling safety.

2.4. User satisfaction and demographics

Understanding user satisfaction and demographics is essential for designing a bike-sharing system that appeals to a wide range of users. Research has shown that factors such as age, income, and education significantly impact the likelihood of adopting bike-sharing systems. Authors emphasize the need to tailor bike-sharing systems to the specific needs of different demographic groups. Younger, more active individuals, for example, may be more inclined to use bike-sharing systems, while older or less physically active users may require additional features such as e-bikes for ease of use. User demographics and experiences are integral to enhancing user satisfaction and improving overall system adoption [21–25]. Safe path at junctions/signals is crucial in ensuring that users feel secure using PBSS, particularly in high-traffic areas where bike lanes and proper traffic management are necessary. Comfortable attire/dress is a factor that influences user participation, especially if bike-sharing systems provide racks and facilities for users to change attire.

2.5. Economic and environmental impacts

Bike-sharing systems have profound economic and environmental implications for urban areas. Several studies have highlighted the positive impacts on urban sustainability. Bernardo (2022) and Cheng et al. (2022) provide evidence that bike-sharing systems reduce traffic congestion and lower greenhouse gas emissions, contributing to cleaner air and a healthier urban environment [26,27]. On the economic front, DeMaio (2009) and Pelechrinis et al. (2017) emphasize that bike-sharing systems can stimulate local economies by increasing foot traffic in commercial areas, creating new job opportunities, and offering users a low-cost transportation option. Moreover, economic evaluations consistently show that PBSS are cost-effective compared to other forms of transportation, which can have a significant impact on urban transportation budgets [28,29]. The economic and environmental benefits of bike-sharing align directly with the criterion of clean air to breathe, as these systems promote a healthier environment by reducing car emissions. They also support good physical and mental health, by encouraging physical activity and reducing air pollution.

2.6. Public policies and regulations

The success and sustainability of bike-sharing systems are heavily influenced by public policies and urban regulations. Authors emphasize that policies providing funding, subsidies, and investments in cycling infrastructure are vital for the development and long-term viability of PBSS. Supportive public policies not only provide the financial backing needed to develop and maintain bike-sharing systems but also ensure that they are integrated into the broader urban mobility system [30–32]. This integration can include efforts to improve safety, accessibility, and equitable distribution of services, which are essential for making bike-sharing systems successful in diverse urban contexts. Regulations that ensure the safety of cyclists and address issues such as weather resistance and infrastructure quality are also essential for maintaining system reliability and user confidence. Public policies and regulations have a direct influence on the safety and accessibility of bike-sharing systems. Strong policies also enhance the system's comfort and convenience, ensuring that the infrastructure is safe, well-maintained, and accessible to all users.

2.7. Challenges and adaptation

Despite the many advantages of bike-sharing systems, they face several challenges that require ongoing innovation and adaptation. Bean et al. (2021) and Lee et al. (2016) highlight the impact of weather conditions on bike-sharing usage, suggesting that infrastructure solutions such as weather-resistant bikes and sheltered stations are needed to ensure system functionality year-round [33,34]. Suchanek (2019) notes that the system's ability to adapt to emerging trends, such as the pandemic-induced shift toward social distancing, is crucial for ensuring its continued success [35]. Adapting the service to changing user needs and circumstances, such as offering contactless features and flexible rental options, ensures that users remain confident in the system's safety and reliability. Addressing challenges like weather and pandemics through adaptive service models enhances user safety and system reliability. It ensures that the system can operate effectively under a variety of conditions, which is essential for long-term success. The review of recent research on public bicycle-sharing systems highlights the multifaceted factors influencing their success. Technological advancements, user preferences, infrastructure design, environmental and economic impacts, and supportive policies are all critical components. Addressing these factors through thoughtful design, policy support, and technological innovation can enhance the effectiveness of bike-sharing systems and contribute to more sustainable and accessible urban mobility solutions.

3. Study area and data collection

Selecting the study area where PBSS operational is crucial for the research. This evaluation will help propose PBSS models for other Indian cities like Bengaluru. Ahmedabad, with its flat terrain, is ideal for cycling, making it a strong market for PBSS. As the fifth-largest city in India, Ahmedabad is known for its robust public transportation system,

including an integrated Bus Rapid Transit System (BRTS) and PBSS. The BRTS features dedicated lanes, segregated bus stops, and automated fare collection for efficient transit, while PBSS provides last-mile connectivity with rental bicycles for short trips. Based on a thorough literature review, the study considers factors such as separate cycle lanes, safe cycle parking, clean air, humidity and temperature, on-street vehicle parking, traffic levels, vehicle speed, accident-prone areas, safety at junctions, flat roads, carrier baskets, comfortable attire, good health, and personal safety. User perceptions of these factors were collected through a questionnaire survey rated on a scale of 1 to 5. The study applied Cochran's formula to calculate the minimum sample size, which was determined to be 384 respondents with a 5 % margin of error, ensuring statistical accuracy. Additionally, subscription data from MYBYK was used to guarantee a representative sample that reflected various user demographics and station locations. Primary data was collected in Ahmedabad with a sample size of 1100. The survey aimed to understand perceptions of PBSS at locations near BRTS and MYBYK stations as shown in Fig. 1. Respondents, including PBSS and BRTS users, rated the existing PBSS, factors influencing cycling, PBSS operations, and bicycle quality and maintenance. Interviews were conducted during peak hours at PBSS stations and BRTS stops. This study also utilizes secondary data collected from MYBYK operational records from the year 2023, which reported a total of 577,228 trips. The data provides insights into ridership patterns, trip durations, and distance traveled, enabling a comprehensive analysis of the PBSS's performance and effectiveness in promoting sustainable urban transport in Ahmedabad. Geographic Information System (GIS) techniques were employed to delineate the zones, facilitating a better understanding of spatial distribution and accessibility of the bicycle-sharing stations.

4. Analysis of user perceptions

The survey data reveals significant insights into the socio-

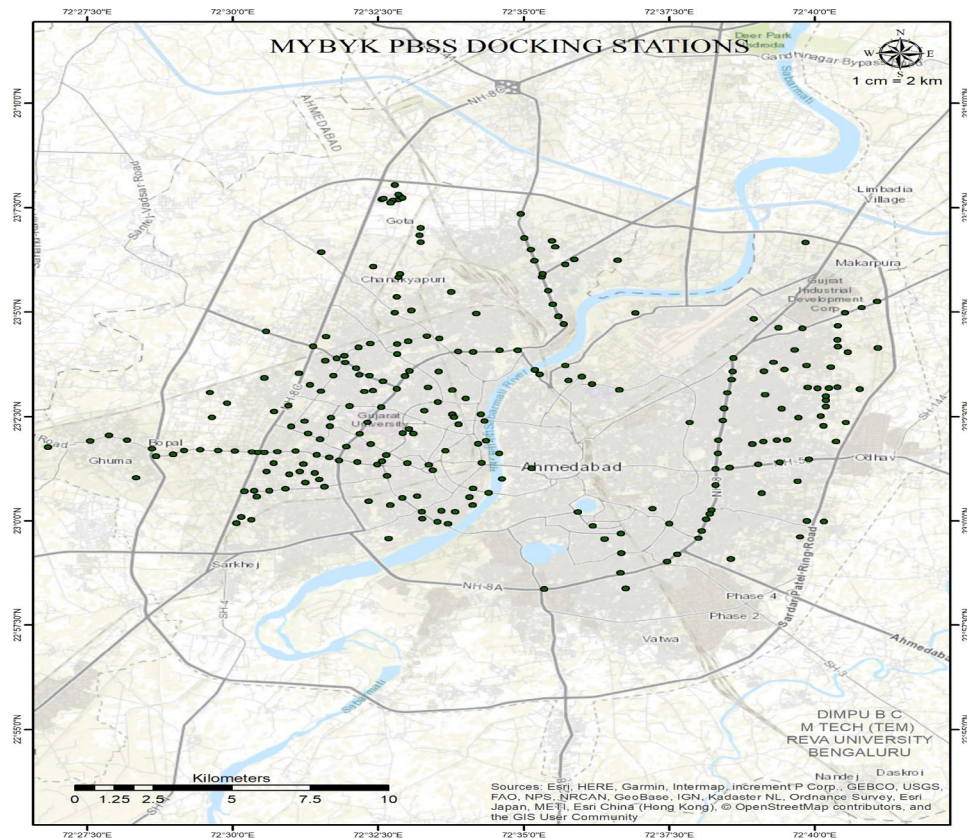


Fig. 1. MYBYK stations in Ahmedabad.

demographic profile of PBSS users in Ahmedabad as shown in Fig. 2. The data shows a strong male dominance in PBSS usage, with 82.47 % of respondents being male. This significant gender disparity suggests that men are more inclined to use cycling as a mode of transportation, likely due to factors such as physical strength, societal norms, and attire. Women's lower participation (17.53 %) may be attributed to concerns about safety, comfort, and the challenges posed by the city's temperature and humidity. The age distribution reveals that the majority of PBSS users are between 20 - 35 years old (57.53 %), followed by those under 20 years (18.08 %) and between 36 - 45 years (14.24 %). This indicates that the younger individuals are more likely to adopt cycling, possibly due to greater health consciousness, environmental awareness, and the need for economical transportation options. A substantial portion of the

respondents are students (40.20 %) and private sector employees (30.34 %), reflecting that PBSS is primarily used by those with flexible schedules or a need for cost-effective transport options. The high percentage of unmarried individuals (64.11 %) further understands the use of PBSS to younger populations. Income-wise, the largest group of income falls between ₹10,001-₹25,000 per month (22.03 %), indicating that PBSS is particularly attractive to lower and middle-income groups seeking cost-effective transport. Overall, the data suggests that while PBSS is popular among younger, male, and financially conscious individuals, there is an opportunity to increase adoption among women, older age groups, and higher-income individuals through targeted initiatives that address specific barriers such as safety, comfort, and convenience.

The PBSS in Ahmedabad, initially aimed at providing a convenient

Socio-Demographic Characteristics of PBSS Users

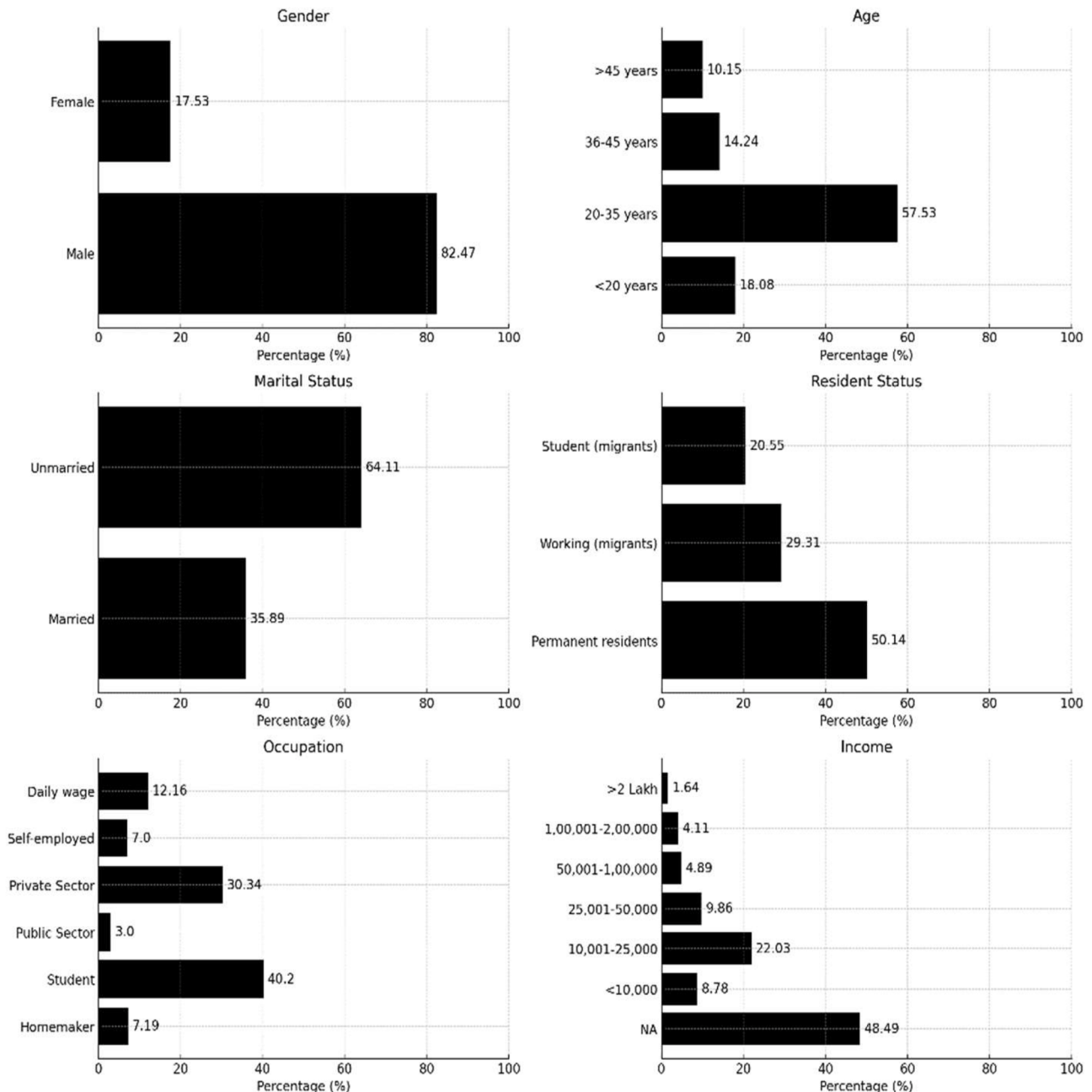


Fig. 2. Socio-demographic details of respondents.

solution for last-mile travel, is predominantly used for leisure (74.41 %) and shopping (64.65 %) as shown in Fig. 3. A notable portion of respondents also use the service for work trips (56.90 %) and educational purposes (40.40 %). While last-mile travel currently accounts for 46.46 % of usage, there has been a recent increase in this segment, driven by incentives, indicating growing acceptance of PBS as a practical commuting option in the city. The PBSS in Ahmedabad, while cost-effective and efficient, faces some financial accessibility challenges, with only 42 % of the respondents feeling comfortable paying the security deposit and ride charges as shown in Fig. 4. A significant portion of users expressed moderate comfort with these costs, indicating a need for more affordability. However, the cycle design, quality, and maintenance were generally well-received, with the majority rating them as good or very good. Only a small percentage of respondents found these aspects lacking, suggesting that the operational side of the system performs well, but financial concerns may be a barrier for broader adoption. The survey reveals that over 80 % of respondents are satisfied with using the Public Bicycle Sharing system for distances greater than 2 km, primarily for leisure purposes as shown in Fig. 5. A strong preference for a carrier basket is evident, with 74 % of respondents favoring it as a necessary fixture. Despite Ahmedabad's flat terrain, 45.6 % of users prefer electric or hybrid cycles, likely due to the city's high temperatures and humidity, which can make cycling less appealing. This suggests that the integrating more electric or hybrid cycles could enhance user comfort and satisfaction with the PBS system.

The user distribution by hour for the PBSS in Ahmedabad reveals distinct patterns in ridership throughout the day as shown in Fig. 6. The data indicates that usage peaks during the early morning hours, with significant activity starting at 5 am and reaching a maximum of 66,415 rides at 6 am, followed by a gradual decline until 10 am. The morning peak captures 29.55 % of total rides between 6 am and 9 am, reflecting a high demand for last-mile connectivity as users head to work or educational institutions. Conversely, ridership diminishes during midday hours, with only 6.72 % of total rides occurring between 12 pm and 4 pm. The afternoon sees a resurgence in usage, particularly between 4 pm and 8 pm, where users engage in leisure activities or return home, culminating in an average of 30,000 rides per hour during this period. The data further indicates a noticeable drop in ridership during the late-night hours, with minimal activity recorded between 12 am and 5 am. Overall, the analysis highlights a clear preference for using the PBSS during the cooler morning and evening hours, suggesting that climatic conditions significantly influence user behavior.

The monthly ridership trend for the PBSS in Ahmedabad as shown in Fig. 7, illustrate fluctuations in usage throughout the year, with a total of 576,261 rides recorded. The trend reveals that the highest number of rides occurred in March, with 68,529 rides, followed closely by April at 64,737 rides. This peak in spring months suggests favorable weather

conditions contributing to increased cycling activity. Notably, June also exhibited a strong performance with 56,364 rides, indicating sustained interest as the summer began. Conversely, the months of July and August experienced the lowest ridership, with only 37,885 and 32,154 rides, respectively. These declines may be attributed to the monsoon season, which often deters outdoor activities due to rain and humidity. The ride data highlights a gradual recovery in the following months, particularly in November with 44,981 rides, suggesting that users resumed cycling activities as weather conditions improved. Overall, the monthly ridership trend emphasizes the seasonal variability in bicycle usage, reflecting the impact of climatic conditions and user behavior on the effectiveness of the PBSS in Ahmedabad.

Geographic analysis of ridership patterns in Ahmedabad categorizes the city into three distinct density zones as shown in Fig. 8, each with its unique characteristics and user behaviors. High Ridership Zone comprises 132 stations primarily concentrated around educational and recreational areas, notably near the university and the Sabarmati riverfront. Users in this zone predominantly engage in short-distance and leisure trips, thanks to the proximity of stations. The high ridership zone shows the greatest acceptance of the Public Bicycle Sharing system, especially among younger users who favor cycling for both recreational and practical purposes. Medium Ridership Zone comprising 86 stations, this zone is primarily located in the eastern part of the city, covering older residential and commercial areas. The medium ridership zone displays moderate usage levels, reflecting a diverse mix of user types who engage in both work and leisure trips. This zone serves as a transitional area between high and low ridership, indicating a balance between accessibility and demand. Low Ridership Zone consists of 35 stations positioned in the northern and southern parts of the city, where overall ridership is comparatively low. The low ridership zone primarily supports work-related trips; however, it struggles to foster significant usage due to limited infrastructure and demand. The lack of essential amenities and connectivity in these areas hinders the growth potential of the PBS system.

To understand the factors influencing cycling as a mode of commute in urban areas, the Analytic Hierarchy Process, developed by Prof. Thomas L. Saaty, is a valuable multi-criteria decision-making tool. AHP helps derive ratio scales from paired comparisons of criteria gathered from surveys and qualitative data. It accommodates minor inconsistencies in judgments due to human error. In the context of cycling, several key criteria are analyzed to understand their impact on cycling adoption. These criteria include the presence of separate cycle lanes, safe cycle parking facilities, clean air quality, temperature and humidity conditions, on-street vehicle parking, traffic levels, vehicle speed, accident-prone areas, safety at junctions, road flatness, availability of carrier baskets, comfortable attire, physical and mental health, and overall personal safety. Each of these factors plays a significant role in

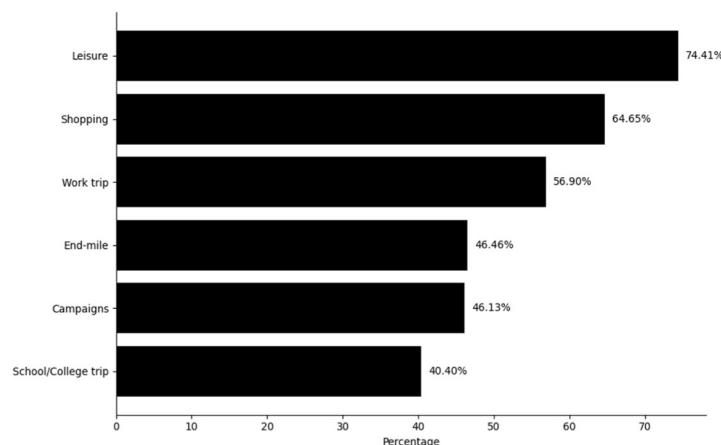


Fig. 3. Primary Purposes for using the PBSS in Ahmedabad.

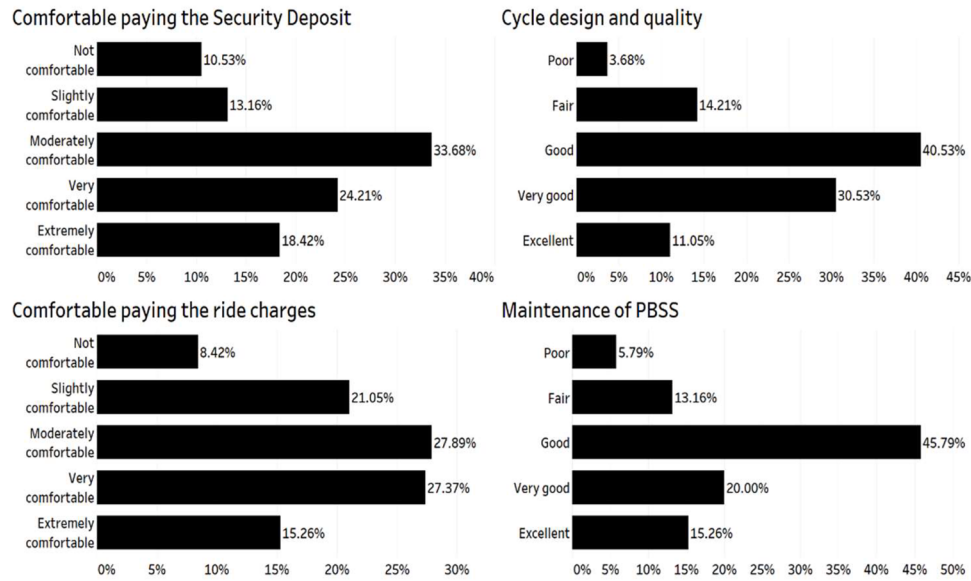


Fig. 4. User perceptions of cost, cycle design, and maintenance in the Ahmadabad PBSS.

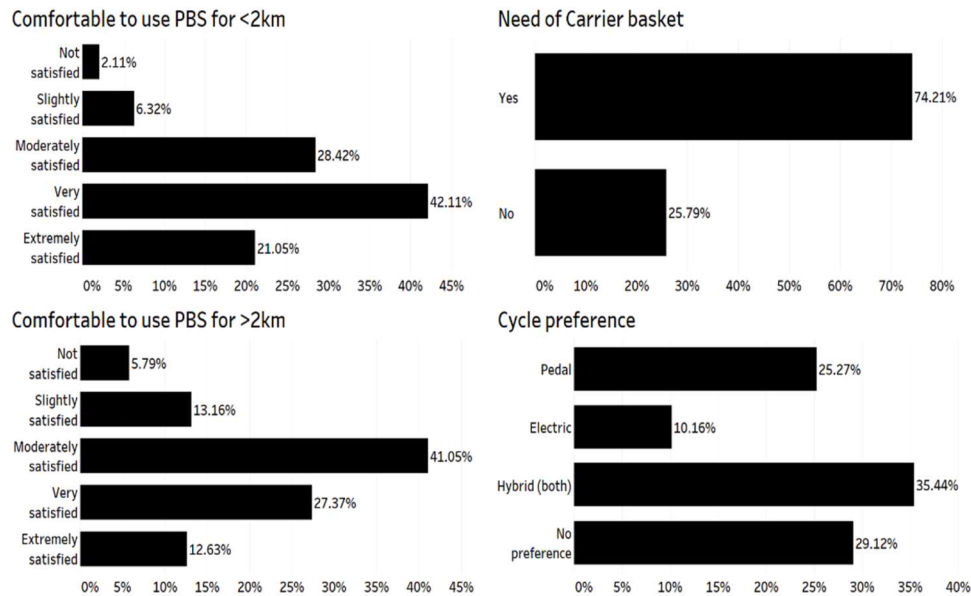


Fig. 5. User preferences for distance, cycle features, and comfort in the Ahmadabad PBSS.

determining the attractiveness and feasibility of cycling as a commuting option in urban areas. To evaluate these criteria systematically, a pairwise comparison matrix as given in Table 1 is created based on expert ratings, using a scale from 1 to 9 to reflect the relative importance of each criterion. This scale indicates the relative importance of one criterion over another, with 1 representing equal importance and 9 (or its reciprocal) indicating extreme preference. This matrix is then normalized to obtain the principal eigenvector as given in Table 2, which provides the ratio scales for the criteria. A crucial step in AHP is checking the consistency of judgments to ensure reliability of the results. This is done by calculating the Consistency Index (CI), which measures how consistent the judgments are compared to a theoretically perfect consistency. The Consistency Ratio (CR), which is the ratio of CI to the Random Consistency Index (RI), must be 10 % or less to be considered acceptable. If the CR exceeds this threshold, the judgments are revised to improve consistency.

The weights reflect the relative importance of each criterion in the

decision-making process for evaluating alternatives in the Public Bicycle Sharing Systems as shown in Fig. 9. The highest weight is assigned to Personal Safety (PS) at 21.40 %, indicating its critical role in influencing users' willingness to participate in bicycle sharing. Safe Path at Junctions/Signals (S-Ju) also holds significant weight at 16.89 %, emphasizing the importance of safe infrastructure. Other criteria such as Good Physical and Mental Health (GH) and Clean Air to Breathe (CA) also play vital roles, highlighting the environmental and health impacts of cycling. In contrast, criteria like Flat Roads (FR) and Humidity and Temperature (H&T) have lower weights, suggesting that while they are still relevant, they may be less critical in the overall evaluation compared to safety and user experience.

5. Evaluation of alternatives

Evaluating alternatives in decision-making processes, particularly in complex scenarios like Public Bicycle Sharing Systems, requires robust

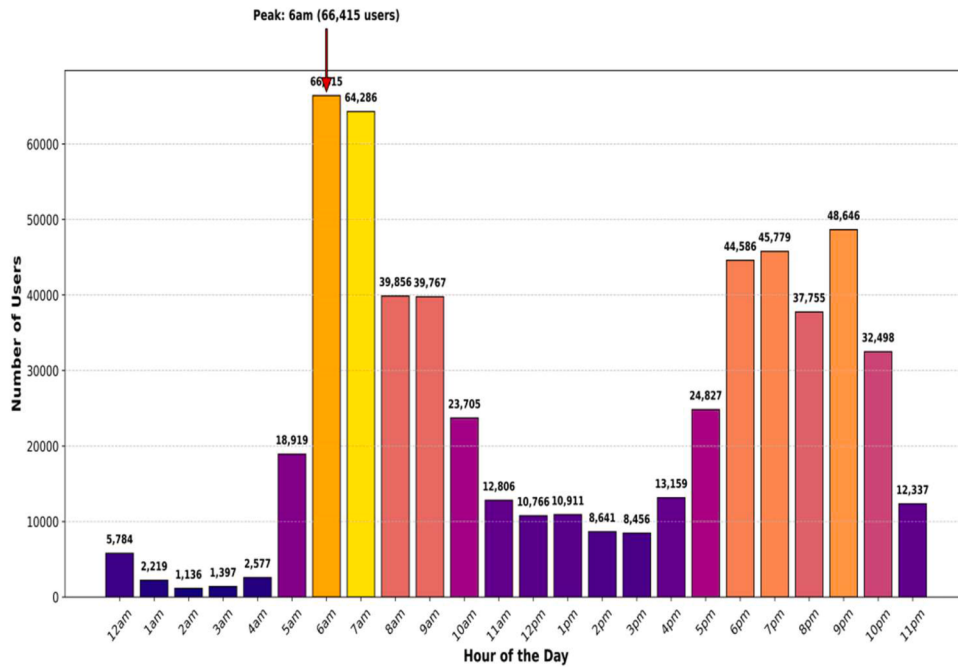


Fig. 6. User distribution by hour.

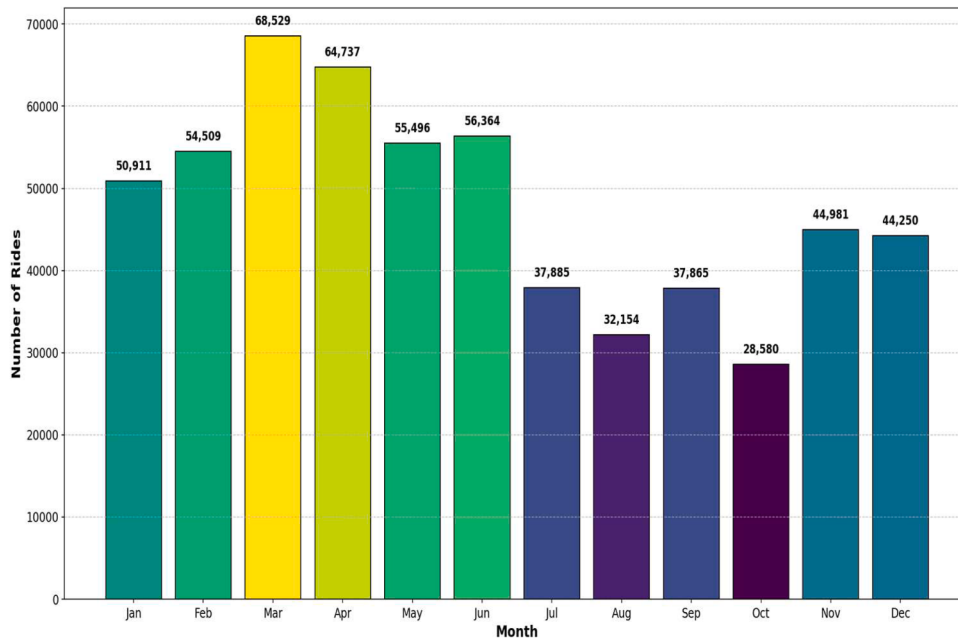


Fig. 7. Monthly ridership trend.

methodologies that can accommodate various criteria and stakeholder perspectives [36]. This study aims to identify the most effective alternative for enhancing PBSS in urban environments by employing four distinct methods such AHP, Fuzzy AHP, ANP and TOPSIS. The five alternatives being evaluated are: 1) Enhanced Non-Motorized Transport (NMT) Infrastructure, 2) Implementation of Slow Streets, 3) Awareness and Education Campaigns, 4) Expansion of Bicycle Network, and 5) Integration with Public Transport. Each alternative represents a different strategy for improving the functionality and accessibility of PBSS, with the ultimate goal of promoting sustainable urban transport. The primary criteria identified for this evaluation included Safety, Environmental Impact, User Convenience, and Infrastructure Quality,

each comprising specific sub-criteria that further delineate the factors affecting the performance of PBS systems. In the Safety, sub-criteria such as Separate Cycle Lanes (SCL), Safe Paths at Junctions (S-Ju), and Personal Safety (PS) were assessed to ensure that cycling infrastructure minimizes risks for users. Environmental Impact focused on Clean Air (CA) and Good Health (GH), emphasizing the importance of promoting sustainable practices that contribute to urban air quality and public well-being. User Convenience encompassed Safe Cycle Parking Facilities (SCPF), On-street vehicle parking (OSP), Carrier Baskets (CB), and Comfortable Attire (CoA), reflecting the need for practical solutions that enhance the overall user experience. Finally, Infrastructure Quality examined factors such as Humidity and Temperature (H&T), Less Traffic

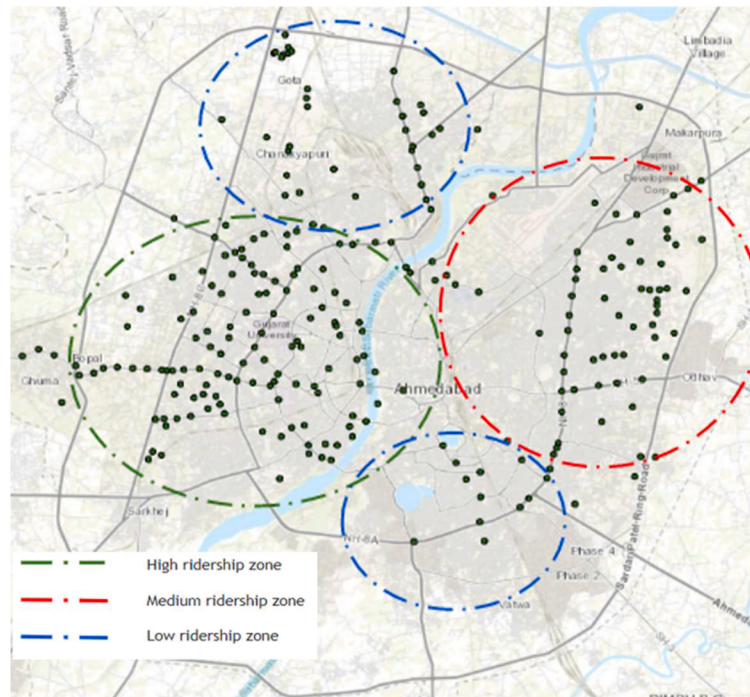


Fig. 8. Density zones of study area.

Table 1

Pairwise comparison matrix for criteria evaluation.

Criteria	SCL	SCPF	CA	H&T	OSP	LT	RVS	MAPA	S-Ju	FR	CB	CoA	GH	PS
SCL	1.00	3.00	0.50	1.40	1.00	0.50	0.50	1.50	0.20	3.00	3.00	1.50	0.33	0.14
SCPF	0.33	1.00	1.00	1.50	1.00	1.00	1.00	1.80	0.20	3.00	1.20	1.50	0.33	0.14
CA	2.00	1.00	1.00	7.00	3.00	1.00	1.00	3.00	0.33	9.00	5.00	3.00	1.00	0.33
H&T	0.71	0.67	0.14	1.00	0.50	0.50	0.50	1.20	0.14	1.20	1.00	1.00	0.33	0.11
OSP	1.00	1.00	0.33	2.00	1.00	0.14	0.14	1.50	0.20	2.00	1.60	1.50	0.33	0.14
LT	2.00	1.00	1.00	2.00	7.00	1.00	1.00	1.50	0.33	3.00	3.00	2.00	0.33	0.33
RVS	2.00	1.00	1.00	2.00	7.00	1.00	1.00	1.50	0.33	3.00	3.00	2.00	0.33	0.33
MAPA	0.67	0.56	0.33	0.83	0.67	0.67	0.67	1.00	0.20	3.00	1.00	1.00	0.33	0.33
S-Ju	5.00	5.00	3.00	7.00	5.00	3.00	3.00	5.00	1.00	9.00	9.00	5.00	1.00	0.33
FR	0.33	0.33	0.11	0.83	0.50	0.33	0.33	0.33	0.11	1.00	0.33	0.33	0.11	0.33
CB	0.33	0.83	0.20	1.00	0.63	0.33	0.33	1.00	0.11	3.00	1.00	0.50	0.20	0.20
CoA	0.67	0.67	0.33	1.00	0.67	0.50	0.50	1.00	0.20	3.00	2.00	1.00	0.20	0.20
GH	3.00	3.00	1.00	3.00	3.00	3.00	3.00	3.00	1.00	9.00	5.00	5.00	1.00	0.33
PS	7.00	7.00	3.00	9.00	7.00	3.00	3.00	3.00	3.00	3.00	5.00	5.00	3.00	1.00

SCL - Separate Cycle Lane; SCPF - Safe cycle parking facilities; CA - Clean air to breathe; H&T - Humidity and Temperature; OSP - On-street vehicle parking; LT - Less traffic; RVS - Reduced vehicle speed; MAPA - Marked accident-prone areas; S-Ju - Safe path at junctions/signals; FR - Flat roads (terrain); CB - Carrier basket for luggage; CoA - Comfortable attire/dress; GH - Good physical and mental health; PS - Personal safety.

(LT), Reduced Vehicle Speed (RVS), Marked Accident-Prone Areas (MAPA), and Flat Roads (FR), ensuring that the built environment supports safe and enjoyable cycling.

The application of four distinct Multi-Criteria Decision-Making methods—AHP, Fuzzy AHP, ANP, and TOPSIS—in this study provides a robust, holistic, and validated framework for evaluating strategies to improve the Public Bicycle Sharing System in Ahmedabad. Each method brings unique analytical strengths and is based on different assumptions that enrich the overall decision-making process. AHP is effective in hierarchically structuring complex problems and deriving priority weights through expert pairwise comparisons of 14 evaluation criteria, such as Personal Safety, Clean Air, and Safe Paths at Junctions. However, it assumes independence among criteria and consistent judgments. Fuzzy AHP addresses this by introducing triangular fuzzy numbers to capture the imprecision and ambiguity in human judgments—particularly for subjective indicators like User Convenience, Humidity & Temperature, or Cycle Parking Facilities—using linguistic terms rather than fixed numerical scales [37]. ANP extends AHP by allowing interdependence

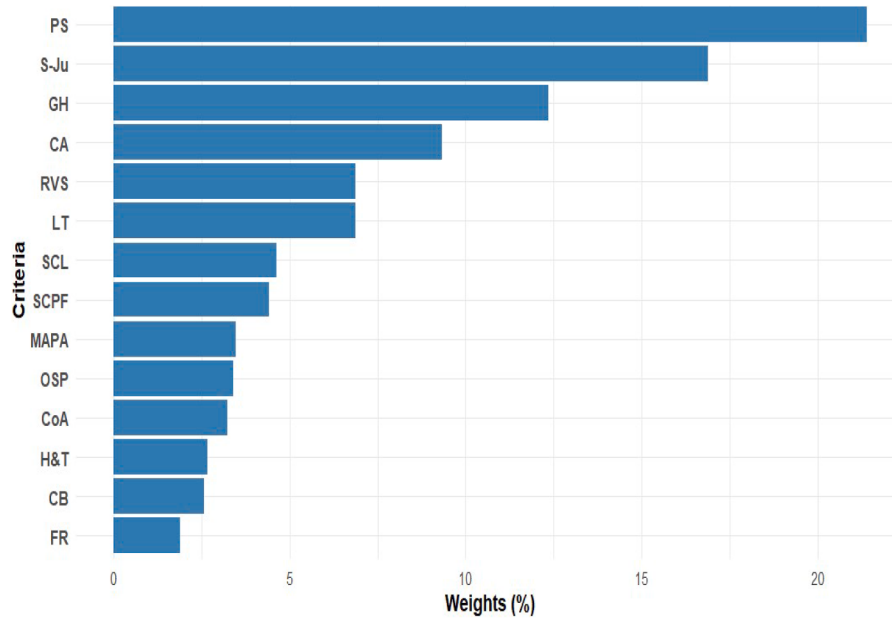
and feedback loops among criteria [38,39]. For instance, in PBSS planning, Safety may influence Infrastructure Quality, and Environmental Impact may affect User Experience. ANP captures these interrelations through supermatrix-based computations, enabling a more realistic network representation. TOPSIS, in contrast, is a performance-based method that evaluates alternatives based on their geometric closeness to an ideal solution, using a normalized decision matrix where alternatives are rated across all criteria [40]. Weights for TOPSIS are adopted from AHP. By integrating these methods, the study captures hierarchical structure (AHP), subjective uncertainty (Fuzzy AHP), systemic interdependence (ANP), and relative performance proximity (TOPSIS). Despite their conceptual differences, all methods consistently ranked Enhanced Non-Motorized Transport Infrastructure as the most preferred alternative, reinforcing the robustness of the results. This integrative approach ensures that all critical dimensions of urban cycling systems are considered, leading to more balanced, inclusive, and sustainable PBSS planning in Ahmedabad and similar urban contexts. The input data used to evaluate and rank the alternatives

Table 2

Normalized matrix for criteria evaluation.

Criteria	SCL	SCPF	CA	H&T	OSP	LT	RVS	MAPA	S-Ju	FR	CB	CoA	GH	PS	EV	W
SCL	0.04	0.12	0.04	0.04	0.03	0.03	0.03	0.06	0.03	0.05	0.07	0.05	0.04	0.03	1.21	4.63
SCPF	0.01	0.04	0.08	0.04	0.03	0.06	0.06	0.07	0.03	0.05	0.03	0.05	0.04	0.03	1.15	4.41
CA	0.08	0.04	0.08	0.18	0.08	0.06	0.06	0.11	0.05	0.16	0.12	0.10	0.11	0.08	1.21	9.34
H&T	0.03	0.03	0.01	0.03	0.01	0.03	0.03	0.05	0.02	0.02	0.02	0.03	0.04	0.03	1.05	2.66
OSP	0.04	0.04	0.03	0.05	0.03	0.01	0.01	0.06	0.03	0.04	0.04	0.05	0.04	0.03	1.29	3.40
LT	0.08	0.04	0.08	0.05	0.18	0.06	0.06	0.06	0.05	0.05	0.07	0.07	0.04	0.08	1.10	6.88
RVS	0.08	0.04	0.08	0.05	0.18	0.06	0.06	0.06	0.05	0.05	0.07	0.07	0.04	0.08	1.10	6.88
MAPA	0.03	0.02	0.03	0.02	0.02	0.04	0.04	0.04	0.03	0.05	0.02	0.03	0.04	0.08	0.92	3.48
S-Ju	0.19	0.19	0.23	0.18	0.13	0.19	0.19	0.19	0.14	0.16	0.22	0.16	0.11	0.08	1.24	16.89
FR	0.01	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.08	1.05	1.89
CB	0.01	0.03	0.02	0.03	0.02	0.02	0.02	0.04	0.02	0.05	0.02	0.02	0.02	0.05	1.06	2.58
CoA	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.04	0.03	0.05	0.05	0.03	0.02	0.05	0.98	3.24
GH	0.12	0.12	0.08	0.08	0.08	0.19	0.19	0.11	0.14	0.16	0.12	0.16	0.11	0.08	1.09	12.35
PS	0.27	0.27	0.23	0.23	0.18	0.19	0.19	0.11	0.41	0.05	0.12	0.16	0.34	0.23	0.91	21.40
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	15.37	100

EV=Eigen Value; W = Weights based on Relative Importance (%).

RI ($n = 14$) = 1.57.CI = $(15.37 - 14)/(14 - 1) = 0.105$ | CR = $0.105/1.57 = 0.067$ | CR < 0.10 | Valid.**Fig. 9.** Weights of evaluation criteria for public bicycle sharing system.

across all four MCDM are presented in Annexure 1.

The AHP method was used to evaluate alternatives for improving Public Bicycle Sharing systems. This method involves structuring the decision-making problem into a hierarchy, consisting of the overall goal, the criteria that influence the decision, and the available alternatives. In this case, four key criteria were identified: Safety, Environmental Impact, User Convenience, and Infrastructure Quality. Each of these criteria was compared in pairs using expert judgment to generate a pairwise comparison matrix. From these comparisons, criteria weights were calculated, reflecting their relative importance in achieving the overall goal. After the criteria weights were determined, each alternative was evaluated in terms of how well they performed against each criterion. The final scores for each alternative were calculated by multiplying their performance scores by the respective criteria weights, and the results were aggregated to obtain a total score for each alternative as given in Table 3. The AHP analysis showed that "Enhanced NMT Infrastructure" was the most preferred alternative, with the highest overall score. This was followed by "Expansion of Bicycle Network" and "Implementation of Slow Streets." Alternatives like "Awareness and Education Campaign" and "Integration with Public Transport" received

Table 3

Ranking alternatives in public bicycle sharing systems as per AHP method.

Alternative	AHP Score	Rank
Enhanced NMT Infrastructure	0.455	1
Expansion of Bicycle Network	0.315	2
Implementation of Slow Streets	0.289	3
Awareness and Education Campaign	0.175	5
Integration with Public Transport	0.185	4

lower scores, indicating a lesser preference for these strategies in the context of improving Public Bicycle Sharing systems [40].

The ANP method was used to evaluate alternatives for enhancing Public Bicycle Sharing systems by considering interdependencies between the criteria. Unlike the AHP, which assumes that criteria are independent, the ANP allows for feedback and relationships between the criteria, making it a more flexible tool for complex decision-making processes. The ANP methodology began by structuring the decision problem into a network of criteria, sub-criteria, and alternatives. In this case, four main criteria were considered: Safety, Environmental Impact,

User Convenience, and Infrastructure Quality. These criteria were evaluated not only based on their importance in relation to the goal but also based on their influence on each other. For example, Safety could impact User Convenience, and Environmental Impact could influence Cost-effectiveness. Pairwise comparisons were conducted between the criteria to generate the necessary input for the ANP model. The weighted supermatrix was then constructed, which captured the interdependencies between the criteria and alternatives. From this, the limiting supermatrix was derived, and the final priorities of the alternatives were calculated by aggregating their performances across all criteria as shown in Table 4. The ANP results showed that "Enhanced NMT Infrastructure" was still the top-performing alternative, but the scores were adjusted to reflect the interdependencies between the criteria. "Expansion of Bicycle Network" and "Implementation of Slow Streets" followed closely in terms of ranking, while "Awareness and Education Campaign" and "Integration with Public Transport" were ranked lower, similar to the results of the AHP analysis but with some variations due to the feedback loops considered in ANP.

The Fuzzy AHP was employed to evaluate alternatives for enhancing Public Bicycle Sharing systems, incorporating the uncertainty and imprecision in expert judgments through fuzzy logic. The methodology began with the establishment of fuzzy pairwise comparison matrices for the criteria: Safety, Environmental Impact, User Convenience, and Infrastructure Quality. Each pairwise comparison was represented using triangular fuzzy numbers, reflecting the subjective assessments of experts. After constructing the fuzzy matrices, the defuzzification process was applied to obtain crisp scores, facilitating the calculation of criteria weights. The final scores for each alternative were computed by aggregating the weighted evaluations based on their performance against the established criteria as shown in Table 5. The results revealed that the "Enhanced NMT Infrastructure" alternative achieved the highest score, indicating it as the most favorable option. Following it were the "Expansion of Bicycle Network" and "Implementation of Slow Streets," which also received significant scores. This analysis underscores the effectiveness of Fuzzy AHP in capturing expert judgments under uncertainty and providing a robust framework for decision-making in sustainable urban transport initiatives.

TOPSIS methodology was employed to evaluate alternatives for enhancing Public Bicycle Sharing systems based on four key criteria: Safety, Environmental Impact, User Convenience, and Infrastructure Quality. The process began with the establishment of a normalized decision matrix derived from the scores assigned to each alternative under the respective criteria. Subsequently, the ideal (best) and negative-ideal (worst) solutions were identified. The separation measures for each alternative were calculated based on their distances to both ideal solutions, allowing for the determination of relative closeness to the ideal solution (C^*). This relative closeness provided a quantitative basis for ranking the alternatives as given in Table 6. The results indicated that the "Enhanced NMT Infrastructure" alternative emerged as the most preferred option, achieving the highest score, followed by "Expansion of Bicycle Network" and "Implementation of Slow Streets." The analysis highlighted the importance of prioritizing infrastructure improvements in promoting effective Public Bicycle Sharing systems.

Across all methods as shown in Fig. 10, Enhanced NMT Infrastructure consistently ranked as the top alternative. This suggests that investments in better Non-Motorized Transport infrastructure are

Table 4
Ranking alternatives in public bicycle sharing systems as per ANP method.

Alternative	ANP Score	Rank
Enhanced NMT Infrastructure	0.460	1
Expansion of Bicycle Network	0.320	2
Implementation of Slow Streets	0.300	3
Awareness and Education Campaign	0.180	5
Integration with Public Transport	0.190	4

Table 5
Ranking alternatives in public bicycle sharing systems as per FuzzyAHP method.

Alternative	Fuzzy Score	Rank
Enhanced NMT Infrastructure	0.475	1
Expansion of Bicycle Network	0.335	2
Implementation of Slow Streets	0.305	3
Awareness and Education Campaign	0.195	5
Integration with Public Transport	0.205	4

Table 6
Ranking alternatives in public bicycle sharing systems as per TOPSIS method.

Alternative	Score (C^*)	Rank
Enhanced NMT Infrastructure	0.480	1
Expansion of Bicycle Network	0.330	2
Implementation of Slow Streets	0.295	3
Awareness and Education Campaign	0.200	4
Integration with Public Transport	0.210	5

universally considered to offer the most significant improvements for public bicycle sharing systems, enhancing safety, convenience, and overall user experience. Expansion of Bicycle Network also scored highly across the methods, highlighting the importance of having an extensive, connected network to encourage cycling in urban areas. Awareness and Education Campaign and Integration with Public Transport were generally the least preferred alternatives, though their rankings varied slightly across methods. This indicates that while education and transport integration are essential, they may not have as direct an impact as infrastructural improvements. The consistency in results across AHP, Fuzzy AHP, ANP, and TOPSIS can be attributed to several factors. Key criteria particularly personal safety and safe paths at Junctions, held significant weight (over 38 %), strongly influencing rankings. Enhanced NMT Infrastructure consistently outperformed other alternatives due to its performance under these critical criteria. Additionally, the preference structure remained stable across methods, with clear gaps between top and lower-ranked options. Despite methodological differences, all methods shared similar mathematical principles and used the same input data, leading to convergent results. This alignment validates the robustness of the evaluation and supports the recommended strategy for improving PBSS in Ahmadabad.

6. Public bicycle insights for transport planners

This study provides valuable insights for transport planners by:

- **Identifying Key Factors:** It highlights the most critical factors, such as personal safety, safe cycling infrastructure, and environmental impact that significantly influence the success of Public Bicycle Sharing Systems. Transport planners can prioritize these factors when designing urban cycling infrastructure.
- **Prioritizing Effective Alternatives:** The study ranks alternatives like enhanced non-motorized transport infrastructure and expansion of bicycle networks as the most effective strategies for improving PBSS. This helps planners allocate resources efficiently to the most impactful interventions.
- **Supporting Decision-Making with Multi-Criteria Methods:** By employing methods like AHP, Fuzzy AHP, ANP and TOPSIS, the study offers a robust, data-driven framework that transport planners can use to make informed decisions in complex urban environments, accounting for interdependencies between criteria.
- **Targeting Socio-Demographic Gaps:** The socio-demographic analysis reveals gender and income disparities in PBSS usage, guiding planners to create more inclusive and accessible transport systems by addressing specific barriers like safety and affordability.

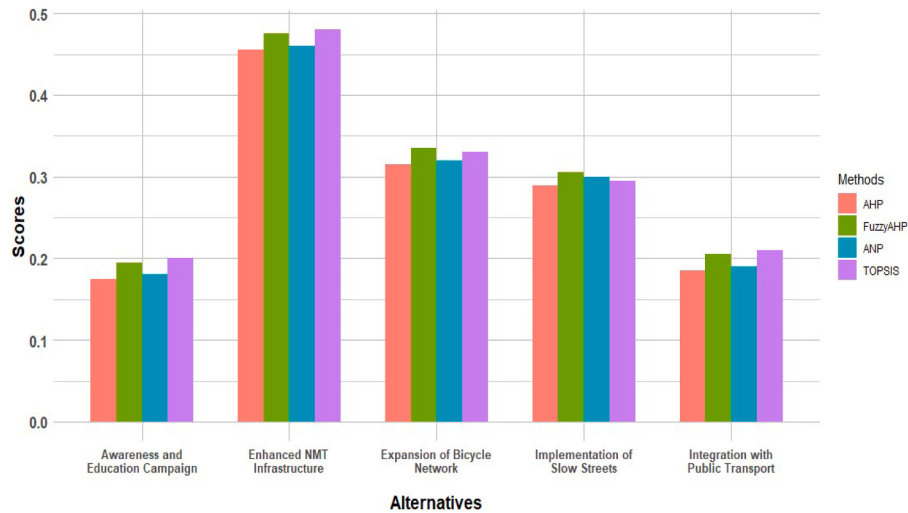


Fig. 10. Comparison of decision-making methods for public bicycle sharing system.

- **Future Urban Mobility Planning:** The study underscores the importance of integrating cycling with existing public transport networks, electric bike adoption, and affordability measures, providing a roadmap for future sustainable urban transport development.

7. Conclusions

The present study mainly focused on evaluating alternatives for improving Public Bicycle Sharing Systems (PBSS) through different decision-making methods such as AHP, Fuzzy AHP, ANP, and TOPSIS. The study identified key factors affecting the success of PBSS, including safety, environmental impact, user convenience, and infrastructure quality. The following conclusions were drawn from the study.

- The socio-demographic analysis reveals a strong male dominance (82.47 %) in the usage of Public Bicycle Sharing Systems (PBSS), with most users being young (ages 20-35) and from lower- to middle-income groups. This indicates a need to address barriers such as safety, comfort, and convenience to encourage greater participation among women, older age groups and higher-income individuals.
- The primary purposes for using the Public Bicycle Sharing System (PBSS) in Ahmadabad are leisure (74.41 %) and shopping (64.65 %), with a smaller percentage of users utilizing the system for work (56.90 %) and educational purposes (40.40 %). This suggests that while PBSS is gaining traction for various activities, there is potential to further promote its use as a practical commuting option.
- User perceptions of the cost, cycle design, and maintenance in the Ahmadabad PBSS are generally positive, with the majority rating the cycle design and maintenance as good or very good. However, financial accessibility remains a challenge, as only 42 % of respondents feel comfortable with the current security deposit and ride charges, indicating a need for more affordable pricing options to broaden the system's user base.
- Despite Ahmadabad's flat terrain, 45.6 % of users prefer electric or hybrid cycles due to the city's high temperatures and humidity, indicating that integrating more electric options could enhance user comfort. Additionally, a strong preference for carrier baskets (favored by 74 % of respondents) highlights the importance of practical features to improve the user experience.
- The analysis reveals a clear monthly variation in ridership, with a total of 576,261 rides across the year. The peak ridership occurred during the warmer months, notably in March with 68,529 rides, while colder months like October recorded the lowest usage at

28,580 rides. This trend emphasizes the influence of seasonal factors on cycling behavior, highlighting the need for targeted promotions and infrastructure enhancements during less popular months to sustain ridership throughout the year. Ridership peaks during morning and evening hours, suggesting that users predominantly utilize the PBSS for leisure and last-mile connections during cooler parts of the day.

- The weights of evaluation criteria show that Personal Safety (21.40 %) and Safe Path at Junctions/Signals (16.89 %) are the most important factors influencing the success of Public Bicycle Sharing Systems. This underscores the critical need for safety-focused infrastructure to encourage greater adoption and user confidence.
- Enhanced NMT Infrastructure consistently ranks as the most effective alternative for improving Public Bicycle Sharing Systems (PBSS) across all decision-making methods. This suggests that investing in better infrastructure, such as dedicated cycling lanes and safer environments, would significantly enhance the adoption and success of these systems.

Future research should focus on increasing inclusivity by addressing gender disparity, improving affordability, and expanding the availability of electric cycles to enhance user comfort in varying climatic conditions. These efforts could further promote PBSS as a practical urban mobility solution.

Statement of compliance with ethical standards

This work is the authors' own original work, which has not been previously published and not currently being considered for publication elsewhere.

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CRedit authorship contribution statement

T.S. Shagufta: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Dimpu Byalal Chindappa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Seelam Srikanth: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Subhashish Dey:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.tbench.2025.100220](https://doi.org/10.1016/j.tbench.2025.100220).

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