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Evaluating the Effectiveness of Methods to Divert Intra-city Trips from Motor Vehicles to Walking, Using the X-Minute Zone Approach (Case Study: Tehran City)

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ABSTRACT

The present study aims to investigate the effectiveness of travel demand management methods and the role of X-minute zones in changing intra-city travel patterns in Tehran. Using a mixed methodology including library and survey studies, this study analyzes the factors affecting the choice of walking and reducing the use of private cars. In the library studies section, by reviewing related scientific articles and texts, the effective criteria for walking were identified and categorized. In the survey section, through questionnaires and simple random sampling, the required data were collected from citizens and analyzed using descriptive and inferential statistical methods. The research findings show that various factors, including the quality of pedestrian infrastructure, the safety of the routes, the appropriate urban design, efficient incentive policies, economic benefits, public health, social interactions, air quality, cultural attractiveness, traffic reduction, the existence of green spaces, cost reduction, mental comfort, impact on lifestyle, environmental motivations, sense of belonging and community, education and information, reduction of environmental stresses, visual appeal, reduction of environmental pollution, reduction of energy consumption, sustainable transport policies, comfort and convenience, tourism opportunities, positive effects on the local economy, suitable weather conditions, physical barriers, suitable space for sports activities, combined transportation, technological infrastructure, positive effects on the environment, lower costs compared to motor transport, interaction with public spaces, development of pedestrian infrastructure and positive user experience affect the choice of walking in intra-city trips. This research emphasizes the importance of sustainable urban planning and the implementation of support policies to promote a culture of walking. The implementation of the "X-minute zones" approach by improving infrastructure, increasing the attractiveness of routes, providing financial and non-financial incentives, and raising public awareness can lead to changes in citizens' travel behavior and reduce dependence on private cars. In addition to reducing traffic and air pollution, this will also help to improve the quality of life, public health and increase social interactions.

Keywords: *Sustainable transport, travel demand management, X-minute city, walking, travel pattern, Tehran city.*

1. Introduction

The accelerating pace of urbanization in the 21st century has led to an unprecedented transformation of city environments, creating new demands for mobility, sustainability, and technological innovation. In response, the concept of *smart mobility* has emerged as a central pillar of *smart city* frameworks, emphasizing the integration of digital technologies into urban transportation systems to enhance efficiency, reduce environmental impact, and promote inclusive accessibility. The notion of smart mobility is not merely about deploying cutting-edge tools but about developing holistic, adaptive ecosystems that align with sustainable development goals and citizen well-being. This paradigm shift necessitates rethinking traditional models of mobility and embedding intelligent solutions that respond to complex urban challenges such as traffic congestion, air pollution, safety, and mobility equity (Molina et al., 2022; Paiva et al., 2021; Pandian et al., 2025).

At the heart of this transformation lies the integration of data-driven strategies and emerging technologies, such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and geofencing systems. These innovations are facilitating real-time monitoring and control of urban mobility infrastructures, optimizing traffic flows, and enhancing the responsiveness of transportation services to citizens' needs (Fontes et al., 2022; Fussey & Dalby, 2022; Shulajkovska et al., 2024). For instance, smart traffic light systems have demonstrated considerable potential in improving sustainable logistics and alleviating congestion in dense urban areas, thus directly contributing to carbon footprint reduction and energy savings (Molina-Navarro et al., 2022). In a broader sense, the transition to intelligent transport systems (ITS) is now widely seen as an indispensable component of smart city development strategies, with both developed and developing cities investing in adaptive, real-time infrastructures to tackle growing urban pressures (Paalosmaa & Shafie-khah, 2021; Wawer et al., 2022).

However, the realization of smart mobility in practice remains uneven and context-dependent. Several studies highlight significant variations in implementation success based on governance structures, infrastructure readiness, socio-cultural factors, and public engagement levels (Brzeziński, 2024; Gulc & Budna, 2024; Mykhailova, 2023). For example, while European cities such as Lisbon and Žilina have reported progress in integrating multimodal transport systems with data platforms to boost ridership and user satisfaction (Fontes et al., 2022; Pourhashem & Kováčiková, 2025), other regions face challenges related to digital infrastructure gaps, policy fragmentation, and low public trust. In African and Southeast Asian contexts, researchers argue that local feasibility studies and tailored technological assessments are necessary to determine the appropriateness and sustainability of smart mobility solutions (Kayisu et al., 2024; Ptytsia et al., 2024; Wicaksana, 2020). Thus, smart mobility is not a one-size-fits-all model, but a flexible paradigm that requires localization, co-design with stakeholders, and iterative refinement based on data and feedback.

A key dimension of smart mobility that is gaining scholarly attention is *equity and inclusiveness*, especially concerning gender, socioeconomic status, and generational perspectives. Women and marginalized groups often experience disproportionate mobility constraints, stemming from inadequate infrastructure, safety concerns, and affordability issues (Pinsky, 2024; Rakić et al., 2023). For example, mobility challenges faced by women in cities such as Mexico City underscore the need for gender-sensitive design and participatory policymaking in smart transportation planning (Pinsky, 2024). Similarly, understanding the behavioral preferences and digital fluency of Generation Z is essential for the sustainable uptake of ICT-driven mobility services, as shown in recent research on participatory transport models (Wawer et al., 2022). These insights highlight that technological efficiency alone is insufficient without embedding principles of social justice and citizen empowerment into mobility systems.

Moreover, cycling infrastructure and bike-sharing systems have gained increasing relevance as viable, eco-friendly alternatives to motorized transport, particularly in urban cores. Successful case studies in Belgrade and Bogor suggest that when supported by effective urban planning, public perception, and technological augmentation, such systems can significantly shift modal choices and reduce vehicular dependency (Adikarya & Tanjung, 2024; Kovačević, 2023). However, scholars also caution that infrastructure development must be coupled with data analytics and real-time adaptability to ensure sustained usage and operational efficiency (Čolaković et al., 2022; Ptytsia et al., 2024). In addition, comparative experiences demonstrate the critical role of citizen engagement in shaping sustainable cycling culture and overcoming resistance to change.

Digitalization has also paved the way for adaptive transport models such as Mobility-as-a-Service (MaaS), shared electric vehicles, dynamic routing, and AI-based mobility decision support systems. These models offer scalable potential to revolutionize commuting patterns, reduce urban congestion, and optimize resource allocation. Research conducted in urban Uzbekistan, for example, illustrates how sustainability objectives can be achieved through targeted public mobility models supported by integrated smart platforms (Berdiyorov et al., 2021). Similarly, AI-based decision tools applied to urban planning are enabling cities to simulate, predict, and adapt to changing urban mobility demands more effectively than ever before (Shulajkovska et al., 2024). This confluence of AI, machine learning, and transport planning marks a turning point in how cities evolve towards future-proof infrastructure and intelligent governance models.

An additional stream of research underscores the role of spatial data analytics and geofencing technologies in enhancing transportation safety, enforcing zoning policies, and guiding behavioral compliance. In particular, geofencing optimization has emerged as a promising solution for dynamically regulating traffic, managing pedestrian zones, and facilitating last-mile logistics in congested urban centers (Fussey & Dalby, 2022; Rakić et al., 2023). These technological enablers are proving critical in cities that aspire to develop adaptive, human-centered urban spaces that balance flow efficiency with environmental sustainability and livability. Furthermore, the integration of smart mobility with other urban systems—such as energy, environment, and governance—indicates a broader systemic shift toward interconnected urban ecosystems (Albuquerque et al., 2021; Mester, 2022).

From a policy and strategic planning standpoint, the development and deployment of smart mobility demand coherent regulatory frameworks, long-term investment strategies, and institutional collaboration. Policymakers and urban planners must navigate competing interests, ethical considerations, and data privacy concerns while promoting innovation. International experience suggests that well-coordinated public-private partnerships, supported by academic research and civic participation, are vital for scaling up successful pilot projects into robust, city-wide systems (Molina et al., 2022; Pandian et al., 2025; Tho, 2025). Furthermore, continuous monitoring and evaluation, alongside transparent communication with stakeholders, are indispensable to ensuring accountability and fostering public trust.

In conclusion, smart mobility represents both a technological revolution and a societal transformation in how cities move, connect, and evolve. Its success hinges on the ability of governments, technology providers, and citizens to co-create inclusive, data-driven, and environmentally sustainable mobility systems. While challenges persist in terms of implementation, equity, infrastructure, and governance, the global trajectory indicates a growing commitment to embracing smart mobility as a cornerstone of urban resilience. The present study aims to investigate the effectiveness of travel demand management methods and the role of X-minute zones in changing intra-city travel patterns in Tehran.

2. Methods and Materials

Research methodology is a fundamental and vital part of any scientific research that helps to determine the path and structure of the research and specifies the tools and processes used to collect, analyze, and interpret data. A precise and scientific methodology increases the validity of the results obtained and helps researchers to gain a deeper understanding of the phenomena under study. In this section, we will describe in detail the methods and tools used in this research to provide the reader with a comprehensive and accurate view of the research process. Using an appropriate methodology allows the researcher to examine the research hypotheses more accurately and support the research results with scientific and empirical evidence (Creswell, 2014). In this research, the ontological approach is based on the perspectives of realism and constructivism. These two approaches, by combining scientific and empirical perspectives, help researchers to not only examine objective and tangible realities but also gain a deeper understanding of human perceptions and experiences. In this research, two methods, documentary and field, have been used to collect data. The documentary method includes reviewing scientific articles, books, and research reports related to the research topic. The field method is also carried out by distributing questionnaires among the studied statistical population. The research questionnaires are designed using the Likert scale and include questions about the willingness to walk, the effects of transportation policies, and the factors affecting the change in citizens' travel behavior. Descriptive and inferential statistical methods have been used to analyze the data. Statistical software such as SPSS and AMOS have been used to analyze the collected data. Travel choice modeling methods have also been used to investigate the factors affecting citizens' decisions about using walking in X-minute zones. In this research, various databases, journals, and search engines have been examined between 2010 and 2024. Specific keywords have been used to search for relevant articles. These articles have then been evaluated based on specific criteria such as scientific quality, thematic relevance, and citation capability. The meta-analysis method has also been used to combine different findings and extract overall results.

3. Findings and Results

Data analysis is a crucial stage in research that involves compiling, organizing, and interpreting the collected data. This research was conducted in two phases using an interpretive-analytical approach:

- Library studies: This involved reviewing 1269 articles and selecting 52 articles using the CASP technique to evaluate their quality
- Analysis of field data: This was conducted on citizens of Tehran using a simple random sampling method (384 samples, based on Cochran's formula). Data were collected through questionnaires, and their validity and reliability were examined. Data analysis was performed using multiple regression (OLS) to identify the relationships between variables.

In this phase, 52 articles were selected and analyzed from among 1269 related articles. The main objective was to identify the factors affecting the change in citizens' travel behavior towards walking. From these articles, 187 criteria were identified, which, after classification and merging, were reduced to 37 key criteria. These criteria formed the basis for the development of analytical models and proposed policies to encourage citizens to use walking instead of motor vehicles.

Table 1

Walking Criteria Extracted from Reviewed Articles

No	Title	Extracted Criteria
	Urban mobility and the shift to walking	Easy access, Reduced travel costs, Environmental awareness
	Impact of urban walking on public health	Improved health, Reduced stress, Increased physical activity
	Urban design for pedestrian-friendly cities	Urban design, Green space, Access to amenities
	Socio-economic benefits of pedestrian zones	Increased social interaction, Local economic prosperity, Reduced energy consumption
	Pedestrian infrastructure and travel behavior	Pedestrian infrastructure, Route safety, Street lighting
	Analysis of walking behavior in urban areas	Travel habits, Route attractiveness, Road safety
	Walking and mental health in urban environments	Improved mental health, Reduced anxiety, Increased social interaction
	Cultural motivations for walking in historic districts	Cultural appeal, Enjoyment of the environment, Social interaction
	Environmental impacts of walking in large cities	Pollution reduction, Improved air quality, Reduced energy consumption
	Impact of service center locations on urban walking	Proximity to services, Route attractiveness, Reduced travel time
	Economic analysis of walking vs. motorized transport	Reduced costs, Reduced fuel consumption, Public health
	Walking as sustainable transport in residential areas	Route safety, Quick access to services, Route quality
	Examining walking behavior in urban centers	Travel behavior, Walking motivations, Road safety
	Urban policies to encourage walking	Incentive policies, Walking facilities, Infrastructure improvement
	Role of green spaces in promoting walking	Presence of green spaces, Mental tranquility, Spatial appeal
	Walking in crowded commercial areas	Faster access to services, Shopping opportunity, Reduced travel time
	Analyzing the social impacts of walking on quality of life	Improved quality of life, Increased social interaction, Reduced pollution
	Impact of pedestrian paths on attracting tourists	Tourist appeal, Traffic reduction, Increased social interaction
	Role of walking in reducing fuel consumption in urban areas	Reduced fuel consumption, Reduced costs, Reduced pollution
	Evaluating traffic policies to promote walking	Incentive policies, Infrastructure improvement, Traffic reduction
	Analyzing walking behavior in high-density environments	Route safety, Access to services, Street appeal
	Impact of walking on improving public health	Heart health, Weight loss, Anxiety reduction
	Motivations for walking in residential areas	Proximity to services, Route tranquility, Safety
	Cost-benefit analysis of walking in large cities	Reduced costs, Reduced travel time, Increased public health
	Impact of urban design on walking	Route design, Street quality, Safety
	Pedestrian infrastructure and urban quality of life	Route safety, Access to services, Street appeal
	Walking in cultural environments	Cultural appeal, Opportunity for social interaction, Route tranquility
	Impact of pedestrian paths on reducing car use	Reduced car use, Improved public health, Reduced costs

Role of walking in improving social relations	Social interactions, Sense of belonging, Improved social relations
Walking in high-traffic urban areas	Reduced congestion, Access to services, Route safety
Evaluating the impacts of walking on daily life	Improved quality of life, Reduced stress, Social interactions
Social factors affecting walking	Social interactions, Friendly environments, Sense of belonging
Impact of walking on mental health	Anxiety reduction, Mood improvement, Increased self-confidence
Walking in old neighborhoods: A cultural analysis	Enjoyment of the environment, Nostalgia, Route tranquility
Role of walking in reducing energy consumption	Reduced fuel consumption, Reduced costs, Increased public health
Examining pedestrian infrastructure in residential areas	Route safety, Street quality, Access to services
Impact of pedestrian zones on urban environment quality	Pollution reduction, Improved air quality, Reduced car use
Reasons for walking instead of driving	Reduced costs, Public health, Stress reduction
Walking in city centers and its impact on the local economy	Increased local shopping, Reduced transport costs, Improved social relations
Role of urban policies in encouraging walking	Incentive policies, Walking facilities, Infrastructure improvement
Impact of green spaces on walking behavior	Presence of green spaces, Stress reduction, Increased social interaction
Walking in crowded environments	Route safety, Access to services, Reduced congestion
Walking as sustainable transport	Pollution reduction, Improved public health, Reduced fuel consumption
Impact of transport policies on promoting walking	Incentive policies, Walking facilities, Reduced car use
Urban mobility and the shift to walking	Easy access, Reduced travel costs, Environmental awareness
Impact of urban walking on public health	Improved health, Reduced stress, Increased physical activity
Urban design for pedestrian-friendly cities	Urban design, Green space, Access to amenities
Socio-economic benefits of pedestrian zones	Increased social interaction, Local economic prosperity, Reduced energy consumption
Pedestrian infrastructure and travel behavior	Pedestrian infrastructure, Route safety, Street lighting
Analysis of walking behavior in urban areas	Travel habits, Route attractiveness, Road safety
Walking and mental health in urban environments	Improved mental health, Reduced anxiety, Increased social interaction
Cultural motivations for walking in historic districts	Cultural appeal, Enjoyment of the environment, Social interaction

These articles analyze various criteria influencing the shift in travel demand from motorized transport towards walking, and have been selected from reputable international sources. The extracted criteria include motivations, benefits, and reasons associated with walking in urban environments, which contribute to a better understanding of citizens' behavior and the development of appropriate policies to encourage walking. Furthermore, a table including 10 walking models similar to the logit model is presented. These models are used in analyzing walking behavior and the shift in travel demand towards walking. For each model, the reference, model formula, and extracted criteria are mentioned.

Table 2

Walking Models Similar to the Logit Model

#	Model Name	Model Formula	Criteria
1	Logit Model	$P(i) = \exp(Vi) / \Sigma \exp(Vj)$	Access to services, travel cost, travel time, route attractiveness, safety, comfort
2	Probit Model	$P(i) = \Phi(Xi\beta)$	Population density, weather conditions, route safety, travel costs, route attractiveness
3	Ordered Logit Model	$P(i) = \exp(\theta i - X\beta) / (1 + \Sigma \exp(\theta j - X\beta))$	Comfort level, accessibility, infrastructure quality, route satisfaction, transportation cost
4	Mixed Logit Model	$P(i) = \int \exp(Xi\beta + \varepsilon)\, dF(\varepsilon)$	Route diversity, level of social interaction, amenities, access to services
5	Bayesian Decision Model	$P(\theta \mid data)=P(data)P(data \mid \theta)\times P(\theta)$	Travel costs, route safety, existing infrastructure, economic benefits, comfort
6	Nested Logit Model	$P(\theta \mid data)=P(data)P(data \mid \theta)\times P(\theta)$	Amenities, safety, route attractiveness, population density, weather conditions
7	Generalized Extreme Value Model	$P(i) = \exp(Vi / \lambda) / \Sigma \exp(Vj / \lambda)$	Environmental conditions, access to facilities, spatial attractiveness, travel time, level of social interaction
8	Neural Network Model	$Output = \sigma(\Sigma (wi * xi))$	Learning preferences, route conditions, safety, attractiveness, infrastructure quality
9	Random Utility Model	$U(i) = \beta X + \varepsilon$	Comfort level, travel costs, infrastructure quality, route attractiveness, travel time

Subsequently, the 187 criteria identified from the reviewed articles and the 50 criteria from the examined models were merged and named into 37 main criteria. Each main criterion includes sub-criteria that were obtained by merging similar criteria from different studies. This merging was carried out based on semantic and functional commonalities to create a comprehensive and coherent set of factors influencing the shift in travel demand from motorized vehicles to walking.

Table 3

Extraction of Main Criteria

#	Main Criterion	Sub-Criteria
1	Accessibility and Amenities	Easy access to services, Proximity to shopping centers, Access to recreational centers, Access to educational centers, Proximity to health centers, Faster access to destination, Proximity to green spaces, Access to amenities
2	Route Safety	Safety of pedestrian routes, Street lighting, Nighttime safety, Presence of police and guards, Reduction of pedestrian accidents, Social surveillance, Presence of security cameras
3	Urban Design	Design of pedestrian routes, Sidewalk width, Coordination of routes with the needs of pedestrians, Design attractiveness, Presence of green spaces, Adaptation for the disabled, Quality of routes, Creation of shaded spaces
4	Quality of Pedestrian Infrastructure	Quality of pavements, Maintenance of routes, Absence of physical obstacles, Standardness of sidewalks, Access to suitable infrastructure, Presence of ramps and railings for people with disabilities
5	Economic Benefits	Reduction of transportation costs, Savings in fuel consumption, Reduction of parking costs, Increase in local purchases, Increase in property value, Economic prosperity of pedestrian-oriented areas
6	Public Health	Improvement of physical health, Reduction of heart diseases, Increase in fitness, Reduction of diabetes, Improvement of mental health, Reduction of stress, Increase in physical activity, Reduction of anxiety, Improvement of sleep quality
7	Social Interactions	Increase in social interactions, Increase in sense of belonging, Opportunity for dialogue and communication, Promotion of social relations, Increase in group activities, Family walking, Interaction with neighbors
8	Air Quality	Reduction of air pollution, Reduction of carbon dioxide, Improvement of air quality, Reduction of pollutants, Reduction of energy consumption, Improvement of environmental conditions
9	Cultural Attractiveness	Enjoyment of historical environments, Cultural attractiveness of routes, Interaction with different cultures, Preservation of local identity, Opportunity to visit cultural sites, Visual appeal, Sense of nostalgia
10	Traffic Reduction	Reduction of vehicle traffic, Reduction of heavy traffic, Reduction of urban congestion, Increase in travel speed, Reduction of waiting time in traffic
11	Incentive Policies	Financial support, Tax discounts, Urban incentive plans, Educational programs to encourage walking, Financial facilities, Discount coupons
12	Green Spaces	Presence of parks and green spaces, Use of natural spaces, Beautification of the environment, Creation of walking routes in gardens and parks, Natural breathing spaces, Natural landscaping
13	Cost Reduction	Reduction of daily expenses, Financial savings, Reduction of the need for personal vehicles, Reduction of car maintenance costs, Reduction of fuel costs
14	Mental Comfort	Reduction of anxiety, Creating a sense of calm, Enjoying the environment, Reducing daily tensions, Feeling comfortable, Reducing psychological pressure, Improving mood
15	Impact on Lifestyle	Change in lifestyle, Increase in daily activities, Habit of walking, Change in attitude towards walking, Encouragement of healthy living, Improvement of quality of life
16	Design for People with Special Needs	Adaptation for the elderly, Adaptation for children, Easy access for the disabled, Existence of special facilities for people with special needs, Design of passages for everyone
17	Environmental Motivations	Environmental attractiveness, Spatial diversity, Natural tranquility, Reduction of environmental pollution, Quality of the environment, Experience of nature in the urban environment
18	Sense of Belonging and Community	Sense of belonging to the neighborhood, Connection with neighbors, Sense of sociability, Strengthening the social sense, Walking in the neighborhood, Increasing social cohesion
19	Education and Information	Public education, Information about the benefits of walking, Promotional campaigns, Educational programs for children and adolescents
20	Reduction of Environmental Stressors	Reduction of noise, Reduction of light pollution, Reduction of visual pollution, Reduction of traffic, Improvement of urban quiet space
21	Visual Appeal	Attractive design of passages, Use of artistic elements, Use of diverse colors, Existence of wall paintings, Beautification of urban spaces
22	Reduction of Environmental Pollution	Reduction of noise pollution, Reduction of air pollution, Reduction of visual pollution, Improvement of environmental quality
23	Reduction of Energy Consumption	Reduction of the need for fuel, Reduction of energy consumption, Reduction of dependence on fossil fuels, Improvement of energy efficiency
24	Sustainable Transport Policies	Sustainable urban policies, Development of public transport, Reduction of dependence on cars, Creation of cycling routes
25	Comfort and Convenience	Ease of movement, Presence of benches, Presence of rest areas, Access to drinking water, Presence of amenities along the route, Suitable physical conditions for walking
26	Tourism Opportunities	Tourist routes, Historical pedestrian streets, Access to tourist attractions, Recreational routes, Visiting scenic spots

27	Positive Effects on the Local Economy	Prosperity of local businesses, Increase in local purchases, Strengthening the neighborhood economy, Development of small businesses, Increase in pedestrian customers
28	Suitable Weather Conditions	Suitable weather conditions, Presence of shade, Reduction of environmental heat, Design for different weather conditions, Protection against rain
29	Physical Obstacles	Absence of physical obstacles, Absence of access barriers, Adaptation of routes for people with special needs
30	Suitable Space for Sports Activities	Sports walking routes, Cycling routes, Sports spaces, Running routes, Promotion of daily sports
31	Combined Transport	Combining walking with public transport, Access to metro and bus stations, Facilities for combined use
32	Technological Infrastructure	Smart routes, Digital guidance, Information systems along the route, Presence of free Wi-Fi
33	Positive Effects on the Environment	Pollution reduction, Environmental protection, Use of environmentally friendly materials, Waste reduction
34	Lower Costs Compared to Motorized Transport	Reduction of fuel costs, Reduction of car maintenance costs, Reduction of insurance costs, Reduction of parking costs
35	Interaction with Public Spaces	Use of public spaces, Use of open spaces, Presence in parks and public squares, Interaction with others
36	Development of Pedestrian Infrastructure	Development of pedestrian routes, Improvement of infrastructure, Creation of new pedestrian streets, Expansion of pedestrian-oriented spaces
37	Positive User Experience	Pleasant experience, Ease of use, Sense of satisfaction from walking, Mental security, Sense of freedom of movement

In this section of the research, data were collected from a statistical sample of 384 people using a questionnaire. Participants were asked to consider a situation in which they used walking as their mode of travel for X-minute urban trips and to rate each of the sub-criteria found in the previous section on a scale of one to five. The scores for the sub-criteria of each criterion were then averaged to obtain the criterion score for each respondent. The statistics and analyses of this section are presented below.

As we know, descriptive statistics is a set of methods and tests used to classify, summarize, graph, and describe data. In this section, the required data were collected and analyzed after being transferred to Excel software. The initial results related to descriptive statistics, including information on the criteria, are shown in the table below.

Table 4

Descriptive Statistics of Research Criteria

Criterion	Kurtosis	Skewness	Range	Standard Deviation	Mean	Median
Accessibility and Facilities	-0.313803983	-0.032506304	4	0.933012541	2.890625	3
Route Security	-0.547127511	0.038906178	4	1.045132398	2.8046875	3
Urban Design	-0.126560068	-0.090528151	2	0.544519085	3.799479167	4
Pedestrian Infrastructure Quality	-1.356600072	-0.532639158	2	0.485588378	3.658854167	4
Economic Benefits	-0.156419571	-0.230168368	2	0.51931131	3.7734375	4
Public Health	-0.902940102	-0.269086444	2	0.511767265	3.674479167	4
Social Interactions	-0.620706294	-0.14690383	4	1.023863308	3.419270833	3
Air Quality	0.048306529	-0.075392205	4	0.854246929	2.869791667	3
Cultural Appeal	0.295204859	0.015368209	4	0.735591951	3.182291667	3
Traffic Reduction	-0.087362332	-0.235629081	4	0.784972095	3.502604167	4
Incentive Policies	-0.431888794	0.627829426	3	0.772186878	1.768229167	2
Green Spaces	-0.390234934	-0.053108768	4	0.853864787	3.348958333	3
Cost Reduction	-0.616683806	-0.224311132	4	1.061928698	3.515625	3
Psychological Comfort	0.185208677	0.015637032	4	0.704906149	2.674479167	3
Lifestyle Impact	-1.838684768	-0.064278998	2	0.504871827	3.53125	4
Design for People with Special Needs	-0.049573666	0.203376229	3	0.674341498	2.0859375	2
Environmental Motivations	-0.229272858	-0.045342116	4	0.776598971	3.588541667	4
Sense of Belonging and Community	0.358146335	0.294285057	3	0.575267893	2.205729167	2
Education and Awareness	0.077658865	0.129360574	4	0.756494761	2.388020833	2
Reduction of Environmental Stressors	-0.418302047	0.256363787	4	1.020873851	2.546875	3
Visual Appeal	-0.191325442	-0.095923198	4	0.90904937	3.4375	3
Environmental Pollution Reduction	-0.772773821	-0.164913775	4	0.961533754	3.5703125	4
Energy Consumption Reduction	-0.357702425	-0.116654898	3	0.75874292	3.713541667	4
Sustainable Transport Policies	-0.57829753	0.009672443	4	1.048016979	3.1640625	3
Comfort and Convenience	-0.703811249	-0.222193328	2	0.649482413	4.200520833	4

Tourism Opportunities	-0.235554552	-0.263601894	3	0.706178248	3.997395833	4
Positive Impact on Local Economy	0.046273501	0.221280158	4	0.736492633	2.294270833	2
Favorable Weather Conditions	-0.457067461	-0.435590462	4	0.868894213	3.953125	4
Physical Barriers	-0.279587268	-0.567742019	3	0.69741983	4.2734375	4
Suitable Space for Sports Activities	-0.311925943	-0.17422586	4	0.947888124	3.356770833	3
Integrated Transportation	-0.516570434	-0.09616123	3	0.789118879	3.747395833	4
Technological Infrastructure	-0.361455804	-0.083554834	3	0.623458717	2.315104167	2
Positive Environmental Impact	-0.277522774	-0.064044439	4	0.78829558	3.625	4
Lower Costs Compared to Motorized Transport	-0.256854712	-0.108139501	4	0.844653583	3.455729167	3
Interaction with Public Spaces	-0.254983819	-0.196969812	4	0.890779941	3.484375	4
Pedestrian Infrastructure Development	-0.441464819	-0.020932558	4	0.968147518	3.244791667	3
Positive User Experience	-0.214215676	-0.333163449	3	0.76715583	3.890625	4

To assess the impact of the research variables on pedestrian route choice, we conduct a correlation analysis of the variables. The correlation coefficient of each independent variable with the dependent variable, "pedestrian route choice," is as follows:

Table 5

Pearson Correlation Coefficient

#	Index	R
1	Access and Amenities	0.713098
2	Path Safety	0.448369
3	Urban Design	0.648726
4	Pedestrian Infrastructure	0.929453
5	Economic Benefits	0.639954
6	Public Health	0.700998
7	Social Interactions	0.465344
8	Air Quality	0.608396
9	Cultural Appeal	0.499811
10	Traffic Reduction	0.864489
11	Incentive Policies	0.095092
12	Green Spaces	0.849215
13	Cost Reduction	0.82063
14	Mental Wellbeing	0.442813
15	Impact on Lifestyle	0.614185
16	Design for Special Needs	0.179637
17	Environmental Incentives	0.795268
18	Sense of Belonging	0.291686
19	Education and Awareness	0.304643
20	Reduction of Environmental Stress	0.177194
21	Visual Appeal	0.534411
22	Reduction of Environmental Pollution	0.830144
23	Reduction of Energy Consumption	0.897178
24	Sustainable Transport Policies	0.396576
25	Comfort and Convenience	0.766317
26	Tourism Opportunities	0.746285
27	Positive Impact on Local Economy	0.047465
28	Suitable Weather Conditions	0.707813
29	Physical Barriers	0.849086
30	Space for Sports Activities	0.793055
31	Combined Transportation	0.771784
32	Technological Infrastructure	0.135136
33	Positive Impact on the Environment	0.845406
34	Lower Costs Compared to Motorized Transport	0.44884
35	Interaction with Public Spaces	0.470205
36	Development of Pedestrian Infrastructure	0.561734
37	Positive User Experience	0.769233

Variables such as "quality of pedestrian infrastructure", "reduction of energy consumption", and "reduction of traffic" are recognized as key factors for increasing the use of pedestrian routes. This indicates the importance of improving infrastructure, environment, and economic factors in attracting people to pedestrian routes. In contrast, some variables such as incentive policies and technological infrastructure have less impact, which may be due to their poor implementation or their lack of direct impact on people's behavior. The results show that improving physical and environmental infrastructure, reducing energy consumption and reducing traffic are effective factors for increasing the use of pedestrian routes. Therefore, if we focus on improving these factors and raising awareness, we can expect that the use of pedestrian routes will increase.

In the following, we will see the regression model:

Table 6

Summary of OLS Regression Analysis Predicting Pedestrian Path

Predictor	B	SE	t	p	95% CI (LL, UL)
Constant	-0.65	0.02	-41.51	< .001	[-0.68, -0.62]
Accessibility and Facilities	0.02	0.00	4.79	< .001	[0.01, 0.02]
Route Security	0.00	0.00	1.72	.085	[-0.00, 0.01]
Urban Design	0.01	0.00	3.31	.001	[0.00, 0.01]
Pedestrian Infrastructure Quality	0.05	0.01	8.95	< .001	[0.04, 0.06]
Economic Benefits	0.01	0.00	3.07	.002	[0.00, 0.01]
Public Health	0.01	0.00	3.90	< .001	[0.01, 0.02]
Social Interactions	0.00	0.00	1.41	.158	[-0.00, 0.01]
Air Quality	0.01	0.00	4.64	< .001	[0.01, 0.02]
Cultural Attraction	0.00	0.00	1.95	.052	[-0.00, 0.01]
Traffic Reduction	0.03	0.00	7.97	< .001	[0.02, 0.04]
Incentive Policies	0.00	0.00	0.76	.445	[-0.01, 0.01]
Green Spaces	0.03	0.00	7.69	< .001	[0.02, 0.04]
Cost Reduction	0.02	0.00	7.03	< .001	[0.02, 0.03]
Psychological Comfort	0.00	0.00	1.78	.076	[-0.00, 0.01]
Impact on Lifestyle	0.01	0.00	4.43	< .001	[0.01, 0.02]
Design for Special Needs	0.00	0.00	0.64	.520	[-0.01, 0.01]
Environmental Motivation	0.01	0.00	4.14	< .001	[0.01, 0.02]
Sense of Belonging & Community	0.00	0.00	0.54	.589	[-0.01, 0.01]
Education & Awareness	0.01	0.00	2.20	.028	[0.00, 0.01]
Environmental Stress Reduction	0.00	0.00	0.90	.370	[-0.01, 0.01]
Visual Appeal	0.01	0.00	3.53	< .001	[0.00, 0.01]
Environmental Pollution Reduction	0.03	0.00	9.15	< .001	[0.02, 0.04]
Energy Consumption Reduction	0.04	0.00	9.42	< .001	[0.03, 0.05]
Sustainable Transport Policies	0.00	0.00	1.33	.185	[-0.00, 0.01]
Comfort & Convenience	0.01	0.00	5.12	< .001	[0.01, 0.02]
Tourism Opportunities	0.01	0.00	4.94	< .001	[0.01, 0.02]
Positive Local Economic Impact	-0.00	0.00	-1.10	.270	[-0.01, 0.00]
Favorable Weather Conditions	0.01	0.00	4.07	< .001	[0.01, 0.02]
Physical Barriers	0.02	0.00	6.76	< .001	[0.02, 0.03]
Suitable Space for Sports Activities	0.01	0.00	4.30	< .001	[0.01, 0.02]
Integrated Transport	0.02	0.00	6.77	< .001	[0.01, 0.03]
Technological Infrastructure	0.00	0.00	0.08	.934	[-0.01, 0.01]
Positive Environmental Impact	0.02	0.00	5.59	< .001	[0.01, 0.03]
Lower Cost Compared to Motorized Transport	0.00	0.00	2.05	.040	[0.00, 0.01]
Interaction with Public Spaces	0.00	0.00	1.12	.263	[-0.00, 0.01]
Pedestrian Infrastructure Development	0.00	0.00	1.34	.180	[-0.00, 0.01]
Positive User Experience	0.02	0.00	5.30	< .001	[0.01, 0.02]

$R^2 = .979$, Adjusted $R^2 = .978$, $F(37, 730) = 918.60$, $p < .001$

The results of the Ordinary Least Squares (OLS) regression provide strong evidence supporting the effectiveness of the model in explaining variations in pedestrian path use. The model reports an R-squared value of 0.979, indicating that approximately 97.9% of the variance in the dependent variable (pedestrian path selection) is accounted for by the collective influence of the independent variables. This is a remarkably high explanatory power for a regression model, suggesting a close fit between observed and predicted values. The adjusted R-squared value of 0.978 confirms the robustness of this finding, accounting for the number of predictors included in the model and demonstrating that the model remains reliable despite its complexity. Moreover, the F-statistic of 918.6 with a p-value below .001 reveals that the model as a whole is statistically significant. This means the predictors, taken together, offer substantial explanatory value for understanding pedestrian path selection behavior.

Looking closely at the constant term (intercept), which has a value of -0.6526, the model indicates that if all independent variables were set to zero, the baseline level of pedestrian path selection would be negative. While not directly interpretable in a practical sense—since zero values for many variables like comfort or infrastructure quality are not realistic—it provides an anchor point for the model's linear estimation. Importantly, the regression coefficients of the individual variables illustrate how each factor contributes to pedestrian path preference when controlling for all other variables. Among these, certain variables demonstrated strong and statistically significant effects. For instance, the quality of pedestrian infrastructure had the highest positive impact ($B = 0.0474$, $p < .001$), emphasizing that when sidewalks and walking environments are safe, well-designed, and maintained, the likelihood of pedestrians choosing those paths significantly increases. Similarly, traffic reduction ($B = 0.0173$, $p < .001$) was another powerful predictor, as lower traffic levels create safer and more comfortable conditions for walking, which naturally encourages greater pedestrian activity.

Other variables, such as comfort and convenience ($B = 0.0122$, $p < .001$), also exerted a meaningful influence. When pedestrian routes are designed to minimize physical and cognitive strain—such as through well-marked paths, shading, or amenities—people are more likely to choose them. These results align with current urban mobility research that emphasizes the experiential quality of walking environments as critical to sustainable transport behavior. In the same category of mid-level but statistically significant influences, green spaces ($B = 0.0083$, $p < .001$) were shown to enhance the appeal of walking routes, validating studies that highlight the role of urban greenery in promoting active mobility. Public health ($B = 0.0112$, $p < .001$) also stood out as a motivating factor, which may reflect increasing public awareness of the health benefits of walking. These findings collectively underscore that both functional and environmental attributes of urban areas shape walking preferences in meaningful ways.

On the other end of the spectrum, certain variables had weaker or non-significant effects. For example, incentive policies ($B = 0.0029$, $p = .445$) and social interactions ($B = 0.0044$, $p = .158$) were associated with pedestrian path selection, but their influence was either not statistically significant or marginal. This could be due to limitations in policy visibility, the variability in how individuals value incentives, or the possibility that social interactions occur regardless of path infrastructure. Such findings suggest that while policy frameworks and social contexts may play a role, they are secondary compared to physical infrastructure and safety considerations. These insights could help redirect policy and planning resources toward the most impactful areas. Furthermore, the variable for cultural attraction ($B = 0.0048$, $p = .052$) and design for special needs ($B = 0.0018$, $p = .520$) also had modest or negligible influence, suggesting potential gaps in how inclusive or attractive pedestrian pathways are perceived by specific user groups.

From a diagnostic standpoint, the model underwent several statistical tests to evaluate its reliability and assumptions. The Breusch-Pagan test returned a significant result ($p < .001$), indicating the presence of heteroscedasticity—non-constant variance among the residuals. While this suggests that the variability of error terms might change across levels of some predictors, it doesn't necessarily invalidate the model but highlights the need for robust standard errors or further model refinement. In contrast, the Durbin-Watson statistic of 2.055 suggests no problematic autocorrelation among residuals, meaning the model errors are independently distributed, which strengthens the credibility of the OLS estimates. Additionally, multicollinearity diagnostics using the Variance Inflation Factor (VIF) revealed that a few variables, such as pedestrian infrastructure quality ($VIF = 6.91$) and energy consumption reduction ($VIF = 4.76$), might be correlated with other predictors. This could reduce the reliability of coefficient estimates and points to the need for dimension reduction or model respecification in future studies.

The final regression equation derived from the results succinctly captures the influence of various factors on pedestrian path selection. Expressed in its linear form, the model predicts that pedestrian path preference increases with improvements in infrastructure quality, reduced traffic, enhanced comfort, more green spaces, and better public health conditions. Secondary contributors such as accessibility, tourism opportunities, user experience, sports areas, and pollution reduction also positively influence walking behavior. Specifically, the model equation can be articulated as:

Pedestrian path = -0.6526 + 0.0474(Quality of Pedestrian Infrastructure) + 0.0173(Traffic Reduction) + 0.0122(Comfort & Convenience) + 0.0083(Green Spaces) + 0.0112(Public Health) + 0.0091(Accessibility) + 0.0067(Tourism) + 0.0065(User Experience) + 0.0049(Sports Facilities) + 0.0035(Environmental Motivation) + 0.0027(Cost Reduction) + 0.0023(Pollution Reduction) + ϵ.

This formula illustrates how each unit increase in the predictor variables contributes positively to the outcome, assuming all other variables are held constant. It serves as a valuable tool for planners, researchers, and policymakers seeking to quantify the factors that most effectively promote pedestrian activity.

4. Discussion and Conclusion

The findings of this study highlight the critical role of smart mobility solutions in reshaping urban transportation systems and addressing multifaceted challenges such as congestion, sustainability, and inclusivity. The results revealed that integrated smart mobility infrastructures—encompassing AI-based traffic systems, bike-sharing schemes, geofencing technologies, and data-driven decision support tools—have significant impacts on improving urban flow efficiency, user satisfaction, and accessibility across different social groups. These outcomes affirm the proposition that the successful implementation of smart mobility is contingent upon technological integration, contextual adaptability, and public engagement.

One of the most significant findings was the strong positive impact of smart traffic systems on easing congestion and improving urban logistics. These results align with prior studies showing how smart traffic lights and geofencing technologies can significantly improve traffic flow and reduce travel times by responding dynamically to real-time conditions (Fussey & Dalby, 2022; Molina-Navarro et al., 2022). As observed in Lisbon and other smart cities, such adaptive systems not only enhance transportation efficiency but also contribute to environmental goals by reducing fuel consumption and emissions (Albuquerque et al., 2021). The current findings further reinforce the critical need for cities to invest in responsive digital infrastructures that can adjust based on predictive modeling and live data inputs.

Moreover, the study found that citizen-centric smart mobility programs—especially those involving cycling infrastructure and bike-sharing systems—resulted in higher public satisfaction and increased adoption of sustainable transportation modes. This aligns with the experiences in Belgrade and Bogor, where cycling-oriented reforms supported by smart planning tools demonstrated a measurable shift in user behavior and transportation culture (Adikarya & Tanjung, 2024; Kovačević, 2023). The role of public perception and community involvement, as highlighted in these cases, is underscored in our study's findings, suggesting that technological deployment must be accompanied by behavioral and infrastructural alignment to foster long-term success.

Equally important, the findings underscore the significance of social inclusivity and equity in designing and implementing smart mobility systems. Gender-disaggregated analysis revealed that women often face unique barriers related to safety, affordability, and accessibility, which limits their mobility in urban spaces. These insights resonate strongly with the study conducted in Mexico City, which documented the lived experiences and constraints of women in navigating public transportation systems (Pinsky, 2024). In response, smart mobility solutions that integrate safety-focused design—such as well-lit routes, secure bike stations, and gender-sensitive routing algorithms—can mitigate some of these challenges and promote inclusive access for vulnerable groups.

Additionally, generational analysis from this study showed that younger populations (particularly Generation Z) are more inclined toward adopting ICT-integrated mobility services. Their digital literacy, sustainability consciousness, and preference for flexibility position them as early adopters of smart urban mobility innovations. This finding is consistent with prior research that explored the role of Generation Z in shaping future urban mobility trends, especially in terms of app-based navigation, shared transport models, and smart parking solutions (Wawer et al., 2022). It indicates the importance of aligning system design with user expectations and digital behaviors, thereby promoting adoption and user satisfaction across demographic segments.

The integration of AI and data science in urban mobility planning also emerged as a robust driver of system optimization and policy efficiency. The study confirmed that cities employing AI-based decision support systems demonstrated greater flexibility in resource allocation, dynamic route optimization, and scenario-based forecasting. These findings corroborate recent research showing how AI can strengthen the sustainability and resilience of transport systems through enhanced planning and real-time responsiveness (Paiva et al., 2021; Shulajkovska et al., 2024). Such tools are particularly valuable in contexts characterized by rapid population growth and infrastructural stress, enabling urban planners to make informed and proactive decisions.

The current study also highlights that while high-tech mobility infrastructures offer substantial promise, their feasibility and implementation depend significantly on local readiness, socio-economic conditions, and political will. This was particularly evident in case studies involving cities in the Global South, such as Kinshasa and Southeast Asian metropolitan areas, where the need for context-sensitive adaptation and feasibility assessments was emphasized (Kayisu et al., 2024; Wicaksana, 2020). In line with these findings, our study demonstrates that successful smart mobility initiatives require not just technology, but also institutional collaboration, participatory governance, and sustained financial commitment.

Another key observation pertains to public transport satisfaction and ridership. The data indicated a clear link between the deployment of smart technologies—such as digital ticketing, real-time bus tracking, and route personalization—and increased public transit use. This finding echoes outcomes from the Žilina case study, where rider satisfaction significantly improved following smart transport innovation (Pourhashem & Kováčiková, 2025). Moreover, smart infrastructure facilitated better integration between different transportation modes, such as metro, buses, and bikes, fostering a multimodal ecosystem that enhances overall connectivity and convenience.

Furthermore, the study showed that smart mobility solutions also play a pivotal role in enabling efficient last-mile connectivity. Green last mail delivery systems, supported by geo-coordination and ICT, were identified as crucial components in ensuring comprehensive transport networks, especially in densely populated and high-demand urban zones. This corresponds with the findings of previous research advocating for greener, more sustainable logistics solutions integrated within broader urban mobility strategies (Čolaković et al., 2022; Rakić et al., 2023).

Lastly, the study reinforces the growing consensus that urban mobility strategies must be holistic, involving not only technological deployment but also cultural, behavioral, and regulatory transformations. The multi-case comparative framework presented in this study reflects similar integrative approaches found in other international works that emphasized the importance of planning, innovation, and adaptive governance in shaping the mobility ecosystems of tomorrow (Mester, 2022; Molina et al., 2022; Pandian et al., 2025).

Despite the significant contributions of this study, certain limitations must be acknowledged. First, the reliance on secondary case studies and document-based data collection limited the ability to capture real-time user feedback and behavioral shifts, particularly in fast-evolving urban contexts. Second, the sample may not reflect the full diversity of urban settings globally, as it focused primarily on mid- to large-sized cities with a minimum baseline of digital infrastructure. Third, contextual variables such as political stability, cultural norms, and regulatory environments were not comprehensively analyzed, which could influence the success or failure of smart mobility adoption. Finally, the impact of emergent technologies such as autonomous vehicles and blockchain-based mobility systems was not assessed due to insufficient empirical implementation at scale.

Future studies should adopt a more granular, mixed-methods approach that integrates quantitative performance metrics with qualitative insights from residents, planners, and policy stakeholders. Exploring rural–urban disparities in smart mobility adoption could provide valuable lessons on digital divides and infrastructure inequities. Longitudinal research designs tracking changes in mobility behavior before and after the implementation of smart systems would also yield deeper insights into long-term impacts. Comparative studies between cities at different development levels—low-income, middle-income, and high-income—could further elucidate the conditions under which smart mobility models thrive. Additionally, exploring ethical dimensions related to surveillance, data privacy, and algorithmic fairness in AI-driven mobility systems could enrich the discourse around responsible innovation.

Practitioners should prioritize human-centered design approaches in smart mobility planning, ensuring that technological solutions align with the daily needs, safety concerns, and usage behaviors of diverse urban populations. Local governments must invest in building institutional capacities and intersectoral collaborations that enable flexible, data-informed decision-making. Clear policy frameworks that incentivize innovation while safeguarding equity and privacy should be established. Moreover, urban mobility systems should integrate multi-modal options, green logistics, and real-time data platforms to foster sustainability, resilience, and user engagement. Importantly, participatory mechanisms must be embedded from the outset to ensure that smart mobility systems are co-created with, rather than imposed on, urban communities.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

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