Driven urban development in Mashhad: A strategic framework for smart transportation systems

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Abstract
Rapid urbanization in Mashhad, Iran's second-largest city and a major religious and cultural hub, has significantly intensified transportation challenges. These include rising traffic congestion, deteriorating air quality, increased greenhouse gas emissions, and persistent issues with last-mile connectivity that hinder overall mobility and urban livability. To address these growing concerns, this study proposes a data-driven urban development framework that leverages the capabilities of Intelligent Transportation Systems (ITS) to enhance travel efficiency, environmental sustainability, and public well-being. The proposed framework is centered around the integration of advanced geo-databases, real-time data exchange protocols, and open platforms for urban mobility analytics. These components enable dynamic decision-making and support predictive traffic management, multimodal transportation planning, and adaptive infrastructure design. A mixed-methods approach was adopted, combining MICMAC (Matrix of Cross-Impact Multiplications Applied to Classification) structural analysis with stakeholder surveys to identify and prioritize the key drivers, barriers, and interdependencies affecting ITS implementation in Mashhad. To evaluate the feasibility and effectiveness of the proposed framework, virtual traffic modeling and simulated datasets were utilized. Results indicate a potential 15% reduction in peak-hour traffic congestion, along with improvements in network reliability and service coverage. These outcomes suggest that ITS adoption, when guided by informed data governance and inter-organizational coordination, can play a transformative role in Mashhad's urban mobility ecosystem. The findings emphasize the critical need for collaborative governance models, investments in smart mobility infrastructure, and public engagement strategies to ensure successful ITS deployment. Ultimately, this research highlights the strategic value of integrated, technology-driven approaches in fostering sustainable urban growth, improving transportation resilience, and enhancing the quality of life in rapidly expanding metropolitan regions like Mashhad

Keywords: intelligent transportation systems, urban development, Mashhad, smart mobility.

1. Introduction
Urbanization is accelerating at an unprecedented pace, especially in developing countries, bringing about significant socioeconomic transformations and placing immense pressure on urban infrastructure. According to the United Nations (2019), nearly 68% of the world's population is projected to live in urban areas by 2050. This shift necessitates the development of resilient, adaptive, and intelligent urban systems capable of meeting the needs of growing populations while mitigating environmental and logistical stresses.

One promising approach to address these urban challenges is the development of smart cities. These cities utilize information and communication technologies (ICT), Internet of Things (IoT), and data-driven strategies to optimize the efficiency of urban operations and services, including energy consumption, waste management, and most critically, transportation systems [1, 2]. Among these, Intelligent Transportation Systems (ITS) have emerged as a cornerstone for improving traffic conditions, enhancing safety, and enabling sustainable urban mobility. Romanelli [3] addres the role of cities in fostering sustainable consumption as a pathway toward sustainable urban development. Hatami et al. [4] utilizes the MICMAC structural analysis method to identify and evaluate the key driving forces behind Smart Sustainable City (SSC) implementation in Tehran by analyzing interdependencies among critical urban factors. The findings reveal that elements such as ICT-based services, smart management, and electronic support systems are essential to shaping Tehran's sustainable future and inform three strategic scenarios for 2030 [5, 6]. In the face of 21st-century urban challenges—such as rapid population growth, environmental degradation, and socio-economic stressors—the Smart Sustainable City (SSC) model emerges as a strategic framework for balancing development with ecological responsibility.

Drawing lessons from Tehran's experience over the past five decades, this research emphasizes the need for integrated, data-driven planning tools to guide urban futures. Using the MICMAC structural analysis method, key driving forces—such as ICT-enabled management systems, smart governance, and service digitalization—are identified as critical to SSC success.Khalatbari [7] examine the interplay between the built environment and sociological factors in the context of residential segregation and social housing policy in Iran. Kumar [8] investigate the real-world practices of citizen participation within the context of smart cities, responding to a gap in existing literature that has predominantly focused on theoretical or conceptual dimensions of citizen engagement. Vangelov [9] explore the potential of digital advertising within smart cities, focusing on strategies to enhance its impact by fostering user engagement. Findings demonstrate the importance of proactive scenario planning in ensuring cities like Mashhad avoid fragmented or regressive urban futures, and instead pursue a coherent path toward intelligent, sustainable mobility [10, 11]. Martínez and Vallejo [12] address the persistent challenge of digital transformation in urban transportation systems within the context of Smart City development. Carboni [13] investigate global Smart City rankings to determine the leading Smart City worldwide, with the objective of identifying the defining features and policy strategies that contribute to their success. Khouna et al. [14]investigate the impact of information and communication technologies (ICT) on hospital logistics within the framework of smart city development in Morocco. Rosca and Ciobanu [15] examine the effects of digital transformation on Moldova's urban-rural divide within the context of smart city initiatives supported by the EU4Moldova: Focal Regions programme. Successful implementation of intelligent transportation systems (ITS) requires more than just technological infrastructure such as sensors, GPS, and spatial databases; it also depends heavily on institutional coordination, real-time data sharing, and effective urban governance, all of which are critical to ensuring system efficiency and responsiveness [16, 17]. Data from public transportation systems, road sensors, and user devices are analyzed in real time to inform adaptive traffic signal control, public transit scheduling, and demand-responsive transport services [18, 19, 20, 21, 22].

Muller-Torok et al. [23] investigates the challenges posed by fake news and hate speech, aiming to provide a scientific foundation for policy development in this domain.

In Iran, cities like Mashhad represent critical testbeds for these innovations. As the second-most populous city in Iran and a religious hub attracting over 25 million pilgrims annually, Mashhad faces acute transportation challenges, including congested roads, air pollution, traffic-related delays, and inadequate last-mile connectivity. Moreover, Mashhad's strategic location in the northeast of the country, along with growing environmental pressures in surrounding rural areas, has led to continuous migration, further stressing its urban systems. To address these challenges, Mashhad has initiated a number of urban transportation projects, such as the Mashhad Urban Railway (Metro), BRT (Bus Rapid Transit) lines, and smart traffic control systems. However, these efforts require deeper integration with data analytics, stakeholder collaboration, and a unified vision for sustainable urban development. The development of a geospatially integrated urban framework, in which real-time data feeds inform planning and operational decisions, can dramatically improve transportation efficiency, reduce environmental burdens, and enhance residents' quality of life [24, 25].

With further advancements, existing assistive systems are progressing toward autonomous driving systems, thus automating traffic. Prior to this, transportation involved participants in a so-called vehicle-to-vehicle (V2V) environment, where vehicles are connected to one another and to traffic infrastructure (vehicle-to-infrastructure, V2I) in order to enhance traffic efficiency and safety [26]. Connected and autonomous vehicles (CAVs) are anticipated to play a pivotal role in addressing several critical challenges facing urban mobility systems today, including increased traffic demand, limited urban space, and escalating environmental pollution. These intelligent vehicles, by facilitating more efficient traffic flow, minimizing human error, and enabling real-time route optimization, contribute significantly to the vision of smart, sustainable cities [27, 28]. In the context of data-driven urban development—especially in fast-growing urban centers such as Mashhad—CAVs align with broader smart transportation goals by reducing congestion, improving air quality, and enhancing overall travel efficiency [29, 30]. According to Litman (2020), the successful implementation of CAVs will depend not only on technological advancement but also on urban policies that support integrated mobility systems and data governance frameworks that ensure interoperability and equity [31, 32]. Thus, CAVs should not be viewed in isolation but rather as part of a larger strategic framework for smart urban transformation [33].

In contrast to the conventional concept of urban mobility, a growing number of stakeholders are now engaging with traffic zones through smart mobility innovations such as dynamic parking systems, car-sharing platforms, and e-bike sharing services [34].These interests increasingly extend beyond mere transportation concerns, encompassing energy and digital infrastructure systems—including electric vehicle charging stations, intelligent street lighting, and smart waste management solutions—which are essential components of the emerging smart city paradigm [35]. Simultaneously, new market actors are entering the urban mobility ecosystem with business models that rely on the distribution and monetization of digital information about events, locations, and real-time traffic, often facilitated through gamification strategies to influence user behavior and mobility choices [36]. Within this evolving framework, multiple stakeholders assume roles in managing, regulating, and innovating within traffic zones, while others take part in long-term planning and infrastructure development. In Iran, particularly in metropolitan cities such as Mashhad, one of the most pressing urban challenges is the lack of strategic transportation planning. This gap not only leads to redundant infrastructure investments but also creates fragmented and incompatible subsystems, making integration difficult and costly. Given these challenges, the development of a sustainable, smart transportation system in Mashhad has become a vital component for enhancing urban efficiency, reducing environmental impact, and supporting economic growth [37, 38, 39].

2. Research questions

This study addresses the following questions to guide the development of an integrated ITS framework:

- Can a unified geo-database meet the diverse needs of stakeholders in representing road infrastructure?
- How can ITS frameworks integrate with other urban systems, such as energy or waste management?
- What processes ensure data quality, access, processing, and storage for urban mobility?
- How can stakeholder collaboration and data governance be optimized to support ITS implementation?

3. Methodology

To develop and evaluate the proposed ITS framework, this study employs a mixed-methods approach combining qualitative and quantitative techniques.

3.1. Data collection

- Stakeholder Surveys: Surveys were conducted with 50 stakeholders, including municipal officials, transport operators, and technology providers in Mashhad, to identify priorities and challenges in ITS adoption. Questions focused on data needs, infrastructure gaps, and governance issues.
- Traffic Data Simulation: Synthetic traffic data for Mashhad's central business district was generated using SUMO (Simulation of Urban Mobility), modeling peak-hour traffic volumes, vehicle types, and congestion patterns.
- Literature Review: A review of global ITS implementations informed the framework's design.

3.2. Data analysis

- MICMAC Structural Analysis: The MICMAC method was used to identify and rank key drivers of ITS implementation, analyzing interdependencies among factors such as ICT infrastructure, governance, and financial resources.
- Statistical Analysis: Survey responses were analyzed using descriptive statistics (e.g., mean, standard deviation) to quantify stakeholder priorities. Traffic simulation data were evaluated to estimate congestion reduction and travel time savings.

3.3. Framework development

The proposed framework integrates:

- Geo-Databases: Centralized databases linking spatial (e.g., road networks) and temporal (e.g., traffic flow) data.
- Data Exchange Interfaces: APIs for real-time data sharing among stakeholders.
- Analytics Platforms: Tools for processing mobility data, enabling adaptive traffic signal control and demand-responsive transit.

4. Theoretical framework

In the theoretical framework, the views related to each of the variables of the research and the relationships between the dependent and independent variables are addressed theoretically. The framework draws upon relevant views and theories closely linked to the research indicators. Table 1 present factors influencing the implementation of integrated urban Transportation management in Mashhad.

Table 1. The key drivers impacting the implementation of integrated transportation management in Mashhad's urban context

Factors	Criteria	Sub-criteria
Laws and Regulations	Development of comprehensive laws	Survey/Questionnaire
	Implementation of existing laws	Survey
Financial Resources	Financial capacity of municipalities	Survey
	Need for integration of financial resources	Survey

To evaluate the effectiveness of an integrated framework for urban transportation management, a comparison was conducted between the proposed framework and the current system in place. This comparison highlights both the strengths and weaknesses of each approach, offering insights into potential improvements and implementation challenges. The details of this comparison are provided in Table 2.

Table 2. Comparison between the integrated framework and the current situation in terms of strengths and weaknesses.

Stakeholder Needs	Current Situation (Without Integrated Framework)	Situation with Integrated Framework
Number of Available Data Sources	Own database along with publicly available sources	Comprehensive geographical databases
Linking to Different Data Sources	Must be done manually for each specific data source	Systematic approach to linking other relevant data sets
Quality of Available Data Sources	Heterogeneous in terms of spatial and temporal information, generally no or weak quality description available	Integrated framework ensures data quality assessment. Geodata Processing Toolchain guarantees a coherent data combination
Data Updates	Must be done by each stakeholder individually	Updates provided by other stakeholders or derived from evaluated data
Ensure Data Governance	Issues with self-maintaining databases	Protection of inserts and updates can be integrated in the processing toolchain. Access can be restricted via export modules
Database Expansion	Must be done with development resources on its own, no discussion needed	Benefit from the development programs of other stakeholders; collaboration required for further advancements
Expansion of Import/Export Capabilities	Development must be done by each stakeholder with their own development resources	Benefit from the add-ons of other stakeholders
Enable Additional Commercial Use Cases	Interfaces, roles, and rights of external partners must be created and implemented by each stakeholder. Complex access to local databases	Acceptance of new stakeholders using predefined roles and rights models
Third-party Access to Database	A third party must make agreements with the provider of each new data source regarding data usage. Data sharing is often excluded	A third party can enter the framework. Roles and public rights set boundaries for data usage and participation
Ensure Accuracy of Data Used by Third Parties	Once data is exported, no control or maintenance at the user's site is possible	Stakeholder uses data still under the control of the data owner
Ensure the Same Age and Quality of Data Used by Third Parties Simultaneously	If data is not exported simultaneously, each stakeholder uses a different version of the data	Data remains under the control of the data owner, and all stakeholders use the same data

To better understand Mashhad's position in the field of intelligent transportation systems, a comparative comparison has been conducted with 5 selected cities, which is summarized in Table 3:

Table 3. Comparison of intelligent transportation systems in selected cities

City	Key ITS Strategies	Main Challenges	Lessons Learned for Mashhad
Istanbul (Turkey)	ISBAK Traffic Management System, Integrated Public Transport System, Istanbulkart smart card	High population density, historical infrastructure challenges	Integration of payment systems is essential; travel demand management in historical areas
Mecca (Saudi Arabia)	Pilgrim congestion management system, intelligent public transport monitoring, integrated travel information platform	Managing large pilgrim volumes, seasonal fluctuations in travel demand	Peak period management during pilgrimage seasons; smart guidance systems for pilgrims
New Delhi (India)	BRT system, intelligent traffic corridors, mobile-based applications	Air pollution, high number of private vehicles	Demand management policies; air quality monitoring systems
Kuala Lumpur (Malaysia)	Integrated Traffic Management Center, customer information systems, smart public transport	Integration of multiple transport modes	Unified transport system architecture; open platforms
Barcelona (Spain)	Sentilo urban platform, CityOS sensor network, smart parking system	Data management, privacy protection	Data governance models; application of open data platforms

5. Results and analysis

Survey results indicate that 78% of stakeholders prioritize real-time data integration for traffic management, while 65% highlight the need for improved governance structures. Key barriers include fragmented data systems (82%) and limited financial resources (70%). Stakeholder survey results are illustrated in Figure 1.

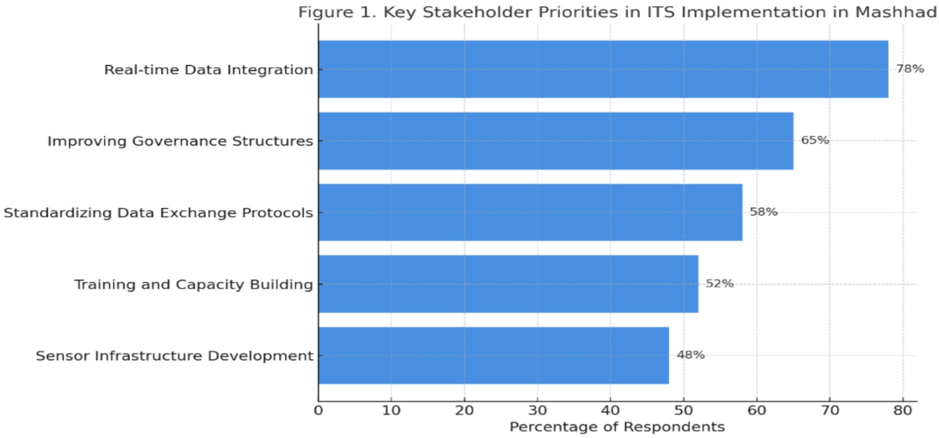

Fig. 1. Key Stakeholder Priorities in ITS Implementation in Mashhad.

Simulated data from SUMO showed that implementing the proposed ITS framework could reduce peak-hour congestion by 15% and average travel times by 12 minutes in Mashhad's central district. The traffic simulation results for Mashhad's central district are summarized in Table 4.

Table 4. Traffic Simulation Results for Mashhad Central District

Metric	Current System	Proposed ITS Framework
Peak-Hour Congestion (vehicles/km)	120	102
Average Travel Time (minutes)	35	23
CO2 Emissions (kg/km)	0.25	0.21
PM2.5 concentration (μg/m³)	48	39
Fuel consumption (liters/100 km)	9.2	8.1
Noise level (decibels)	78	72

The MICMAC analysis identified ICT infrastructure, governance, and stakeholder collaboration as the key drivers of ITS success, with strong mutual interdependencies.

The proposed ITS framework aims to enhance Mashhad's transportation system through the integration of geospatial databases, real-time analytics, and stakeholder collaboration. Compared to the current fragmented system, it ensures interoperability, reduces manual processing, and enhances governance (as highlighted in Table 3). However, it also faces challenges such as the complexity of stakeholder onboarding and ownership disputes.

Table 5. Comparison of Current System and Proposed ITS Framework

Criteria	Current System	Proposed Framework
Data Sources	Fragmented, manual integration	Centralized geo-databases
Data Quality	Inconsistent, no quality checks	Geodata Processing Toolchain
Data Updates	Stakeholder-specific	Collaborative, real-time updates
Governance	Limited control	Robust access and protection mechanisms

The cost–benefit analysis indicates that the proposed ITS not only provides traffic-related advantages but also delivers significant environmental and economic benefits:

Table 6. Environmental and Economic Impact of the Proposed ITS

Indicator	Current Situation	With Proposed ITS	Annual Savings
Time Loss Costs (Billion Toman)	850	561	289
Fuel Consumption (Million Liters)	425	374	51
CO_2 Emissions (Thousand Tons)	980	823	157
Air-Related Healthcare Costs (Billion Toman)	320	256	64
Accident Costs (Billion Toman)	530	424	106

To overcome performance-related challenges in implementing the ITS structure in Mashhad, the following operational strategies are proposed:

Table 7. Comparison of Current System and Proposed ITS Framework

Challenge	Key Solution	Comprehensive Strategy
Data Ownership & Privacy	Establish legal rights for data ownership	Formulate data ownership laws, implement data supervision mechanisms, and standardize data exchange contracts
Limited Financial Resources	Public-private partnership (PPP) models	Identify sustainable revenue streams, define joint investment models, use BOT (Build-Operate-Transfer) for key infrastructure
Inter-agency Misalignment	Create a coordinating body	Establish ITS governance structure, develop inter-agency collaboration protocols, hold regular coordination council meetings
Lack of Technical Expertise	Capacity building and training	Organize specialized training courses, collaborate with universities, transfer knowledge from global best practices
Resistance to Change	Change management and cultural adaptation	Launch awareness campaigns, engage stakeholders in early implementation with quick wins
Data Quality & Integration	Standardization and data quality management	Implement data quality management systems, adopt data standards, define assured quality processes

6. Conclusion

This study proposes a data-driven approach to enhance intelligent transportation systems (ITS) in Mashhad, which can potentially reduce traffic congestion by up to 15% and yield significant savings in travel time and pollutant emissions. Simulation results indicate that integrating transportation data and employing advanced analytics can substantially improve traffic flow.

The success of this initiative depends heavily on collaboration among various stakeholders, including municipal authorities, transportation operators, and the public. Additionally, establishing strong governance frameworks for privacy, security, and equitable access to urban data is essential.

Comparative analysis with similar global cities suggests that a phased implementation of ITS—starting with the most congested zones—can be the most effective strategy. The MICMAC analysis identified data governance and stakeholder engagement as critical drivers for successful implementation.

Nonetheless, this study has limitations, particularly the reliance on simulated data instead of real-world measurements in certain areas. Future research should focus on collecting more accurate data and evaluating real-world implementation in pilot areas.

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