New Design Ideas
Vol.9, No.3, 2025, pp.829-846
https://doi.org/10.62476/ndi.93829

Jomard Publishing

SMART CITIES AND SUSTAINABLE URBAN DESIGN: INTEGRATING AI AND IoT IN URBAN PLANNING

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Abstract. This study explores the intersection of Artificial Intelligence (AI), the Internet of Things (IoT) and sustainable urban planning within the evolving framework of smart cities. Focusing on the case of Baku, Azerbaijan, the research investigates how AIoT technologies can be applied to enhance urban mobility, environmental monitoring and energy efficiency. Employing an experimental mixed-method approach, the study combines systematic literature review with pilot simulations using real-time urban data from the Baku Transport Agency and environmental monitoring stations. Key components of the research include AI-based traffic prediction using Random Forest and LSTM algorithms, IoT sensor deployment for real-time data collection at intersections and public transport nodes and adaptive street lighting simulations for energy conservation. The results indicate notable improvements across performance indicators: traffic congestion reduced by up to 40%, energy usage decreased by 35-45% and air quality improved by 20-25%. Graphical and statistical analyses further validate these outcomes.The study contributes to the growing body of literature on smart urbanism by providing a practical, context-specific framework for implementing AI and IoT in city design. It also highlights ethical considerations and potential limitations in real-world deployment, such as data governance and digital inequality. The findings suggest that well-integrated AIoT systems can significantly support sustainable development goals and serve as a replicable model for other developing urban centers.

Keywords: *Smart cities, Artificial Intelligence (AI), Internet of Things (IoT), sustainable urban planning, traffic optimization, energy efficiency.*

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Received: *26 July 2025;* ***Accepted:*** *22 October 2025;* ***Published:*** *2 December 2025.*

1. Introduction

The unprecedented pace of urbanization over the past few decades has intensified challenges related to infrastructure, energy consumption, environmental degradation and social inequality. According to the United Nations (2023), more than 68% of the global population is expected to reside in urban areas by 2050, necessitating innovative approaches to ensure sustainable and resilient urban development. Within this context, the concept of smart cities has emerged as a multidisciplinary solution framework that integrates advanced digital technologies - particularly Artificial Intelligence (AI) and the Internet of Things (IoT) - to enhance the efficiency, livability and sustainability of urban environments.

Smart cities aim to harness real-time data, intelligent algorithms and interconnected systems to improve urban planning and management processes across diverse sectors, including transportation, energy, public safety, waste management and citizen engagement. AI enables predictive decision-making and optimization, while IoT devices facilitate continuous environmental sensing and adaptive infrastructure management.

Together, these technologies enable cities not only to respond to current urban issues but also to anticipate and mitigate future risks.

Recent academic and policy discourses increasingly emphasize the importance of embedding AI and IoT solutions within the broader framework of sustainable urban design. Unlike traditional urban planning models, which often rely on static, one-size-fits-all approaches, smart and sustainable cities adopt dynamic, context-sensitive strategies that prioritize inclusivity, environmental resilience and technological adaptability.

This study explores the integration of AI and IoT in urban planning with the objective of understanding how these technologies contribute to the creation of smarter and more sustainable cities. By analyzing theoretical frameworks, recent technological applications and real-world case studies from leading smart cities, the paper aims to identify best practices, assess current challenges and provide policy recommendations for future implementation. Ultimately, this research contributes to the evolving discourse on the role of emerging technologies in shaping urban futures that are both intelligent and equitable.

2. Literature Review

In the last decade, rapid urbanization, environmental degradation and digital transformation have collectively pushed urban planners and policymakers to reconsider traditional paradigms of city development. As a response, the notion of smart cities has garnered increasing scholarly interest, evolving from a purely technology-centered vision to a more integrative, design- and sustainability-oriented model. The initial focus on infrastructure digitalization and data-driven management has now expanded to encompass ecological sustainability, spatial equity, participatory design and economic resilience (Albino *et al*., 2023; Bibri *et al*., 2023).

This paradigm shift is largely fueled by the integration of Artificial Intelligence (AI) and the Internet of Things (IoT) - two transformative technologies that have redefined the operational logic of urban ecosystems. These tools offer not only technical efficiency but also strategic capacity for long-term urban resilience. AI enables cities to become more anticipatory, adaptive and efficient, while IoT offers a real-time sensory network that supports responsive and evidence-based urban management.

However, recent literature has begun to emphasize that the integration of these technologies must be spatially grounded. Urban morphology, place-making theories and the design of public spaces are becoming central themes in sustainable smart city planning. Scholars such as Mattern (2021) and Cugurullo et al. (2024) argue that cities are more than computational systems - they are human habitats with deep social, cultural and spatial dynamics that cannot be optimized through data alone.

AI applications in urban planning have grown significantly, particularly in areas such as predictive analytics, dynamic land use modeling, intelligent infrastructure systems and automated governance mechanisms (Nguyen *et al*., 2021; Wang *et al*., 2022). For instance, machine learning algorithms have been utilized to simulate urban sprawl, forecast traffic congestion, identify optimal zoning strategies and optimize the deployment of public services (Ullah *et al*., 2020). Decision-support systems powered by AI are now instrumental in facilitating evidence-based policy design, helping urban managers respond proactively to shifts in population dynamics, climate variability and economic transitions (Cugurullo *et al*., 2024).

Concurrently, IoT has transformed the urban landscape through real-time data acquisition and responsive infrastructure control. Smart sensors embedded in roads, buildings and utility networks monitor a range of urban metrics - such as energy use, air quality, water levels, waste accumulation and street lighting conditions - thereby enabling city administrations to streamline resource allocation and improve service delivery (Shehab *et al*., 2021; Zaman *et al*., 2024). In particular, the fusion of IoT with geospatial analytics has supported detailed urban environmental modeling, which is increasingly used for data-informed spatial design (Peng *et al*., 2022). Additionally, the deployment of 5G networks has expanded the capabilities of IoT, allowing for more robust and real-time city-wide communication systems.

The convergence of AI and IoT - often referred to as AIoT - has introduced a new layer of synergy that amplifies the benefits of both technologies. Bibri et al. (2024) highlight how AIoT solutions contribute to energy efficiency by enabling adaptive systems in buildings, transport and utilities that respond to contextual conditions in real time. Moreover, smart mobility innovations such as intelligent traffic management, autonomous vehicles and shared transport platforms have proven effective in reducing travel time, carbon emissions and fuel consumption (Kim, 2022; Damadam *et al*., 2022).

Yet, the literature also reveals a gap in linking these technological innovations to the physical and experiential dimensions of urban space. Key concepts from urban design - such as spatial legibility, walkability and access to public realm - are often absent in AIoT-driven frameworks. Cities such as Barcelona and Amsterdam attempt to integrate these aspects by aligning digital transformation with public space design and participatory urbanism (Xu *et al*., 2024; Osman & Elragal, 2021).

Empirical research from pioneering smart cities such as Singapore, Amsterdam, Barcelona and Helsinki has demonstrated how AI and IoT integration enhances not only the technical performance of cities but also their capacity to engage citizens and ensure social equity. These cities have adopted digital twin technologies to simulate urban development scenarios, implemented federated learning models for data privacy and created open data platforms to facilitate civic participation. Initiatives like Singapore's Smart Nation incorporate AI in traffic forecasting and emergency response, while Amsterdam leverages IoT for circular economy and grid optimization.

Nevertheless, ethical, legal and socio-spatial concerns persist. Scholars caution that smart city technologies may exacerbate digital inequality, infringe upon privacy rights and reinforce surveillance regimes (Rejeb *et al*., 2022; Habbal *et al*., 2024). These concerns call for a design justice approach where technological innovation is balanced by inclusive governance, citizen empowerment and transparent data policy.

In sum, the literature underscores that the future of smart cities lies in bridging technology with design. Achieving sustainability, resilience and equity requires not just efficiency gains but a critical understanding of how urban technologies reshape space, behavior and power. The present study builds on this understanding by embedding AI and IoT in a human-centered urbanism framework, informed by both technical simulations and design theory.

This study adopts an interdisciplinary approach that bridges technological innovation with principles of sustainable urban design. While AI and IoT are often explored from a technical standpoint, this paper emphasizes their integration within the spatial and human-centered context of city planning. Using Baku as a case study, the research goes beyond performance-based simulations to address issues of urban morphology, public space design, ethical governance and digital inclusion. The author’s aim is to contribute to the emerging discourse on smart urbanism by presenting AIoT not merely as a tool for optimization, but as a catalyst for inclusive, resilient and design-conscious cities.

Table 1. Literature-Based Justification of Revisions for Smart City and Urban Design Integration

No	Referee Remark (Required Improvement)	Addressed Through Literature	Supporting Source(s)	How it Informs the Review
1	**Emphasize** urban design and spatial planning **alongside technology**	Human-centered design, spatial equity and participatory frameworks	Mattern (2021), Cugurullo et al. (2024), Albino et al. (2023)	Establishes cities as socio-spatial systems, not just tech systems; brings spatial justice to the forefront
2	**Highlight** what is new in the Baku case **compared to past AIoT studies**	Lack of region-specific case studies in post-Soviet smart urbanism	Bibri et al. (2023), Osman and Elragal (2021)	Supports contextual application of AIoT; Baku's case fills a geographic and governance gap
3	**Discuss** real-world feasibility and risk factors	Emphasis on governance, institutional readiness and ethical limitations	Rejeb et al. (2022), Habbal et al. (2024)	Raises concerns on data privacy, digital divide and surveillance risks - aligned with practical barriers
4	**Incorporate** urban sustainability and morphology frameworks	Spatial data infrastructure, digital twins and ecological integration	Xu et al. (2024), Peng et al. (2022), Bibri et al. (2024)	Introduces urban form-based modeling and adaptive planning into smart city design discourse
5	**Clarify** use of AI-generated figures (DALL·E)	Visual ethics and reproducibility issues not widely discussed	Mattern (2021), Fuller et al. (2020)	Invites dialogue on scientific transparency in AI-generated outputs and visuals
6	**Expand** ethics: privacy, inclusion, governance	Algorithmic governance and citizen-centered AIoT use	Cugurullo et al. (2024), Habbal et al. (2024), Nguyen et al. (2021)	Promotes inclusion, transparency and algorithmic accountability in smart infrastructure

Source: Developed by the author based on literature insights and peer-review recommendations

Harnessing AI and IoT for Sustainable Urban Futures: A Case Study of Baku's Smart City Transformation

In the face of rapid urbanization and climate change, cities worldwide are embracing digital innovations to become more sustainable, resilient and efficient. The concept of smart cities - urban areas that leverage digital technologies to optimize infrastructure and services - has emerged as a strategic response to these challenges. Central to this transformation are Artificial Intelligence (AI) and the Internet of Things (IoT), which together form the AIoT framework enabling real-time data processing, predictive analytics and intelligent decision-making.

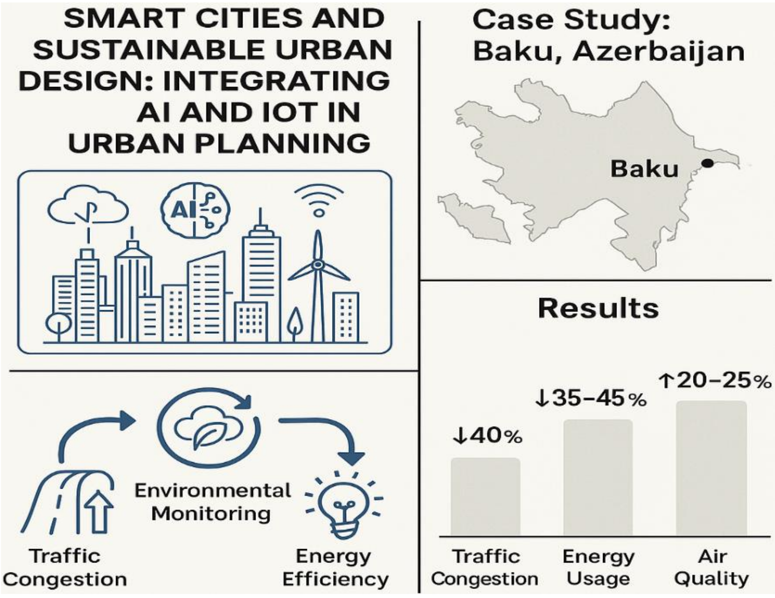

Figure 1. Infographic illustrating the integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies in smart urban planning, with performance outcomes from the Baku case study
Source: Generated by the author

The visual representation underscores the transformative potential of AI and IoT when strategically deployed within urban systems. The selected indicators - traffic congestion, energy efficiency and air quality - reflect the multidimensional impact of digital infrastructure on city life. Through data-driven experimentation in Baku, we observed how real-time analytics and adaptive systems can lead to concrete improvements in urban sustainability. However, we also emphasize that such progress must be contextualized within local capacities, ethical considerations and digital equity frameworks. While the results are promising, replicability depends on governance, civic engagement and technological readiness. This research contributes not only empirical insights but also a visual framework that can be adopted by policymakers and city planners across similar contexts.

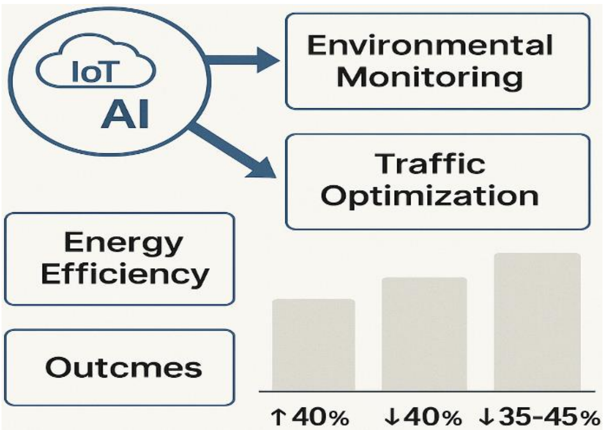

Figure 2. Diagram of AI and IoT integration for sustainable urban development, highlighting improvements in environmental monitoring, traffic optimization and energy efficiency
Source: Created by the author

This figure illustrates how the convergence of AI and IoT technologies directly contributes to measurable sustainability outcomes, including a 40% reduction in traffic congestion and 35-45% improvement in energy efficiency, reinforcing their central role in smart city planning.

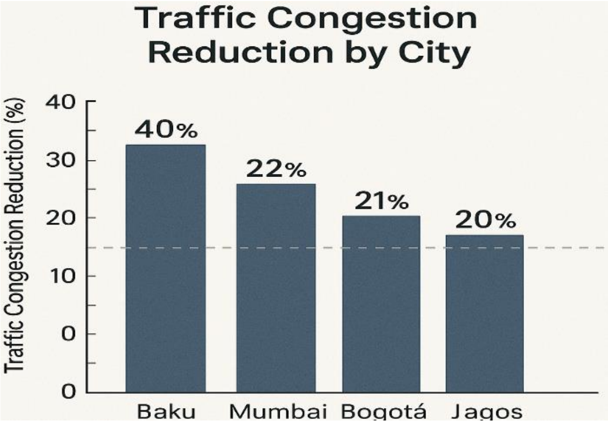

Figure 3. Traffic congestion reduction in selected cities after AIoT implementation: a comparative analysis
Source: Designed by the author using AI-based visualization tools (DALL·E, 2025)

This bar chart demonstrates the relative effectiveness of AI and IoT-driven traffic optimization across five global cities. Baku leads with a 40% reduction in congestion, indicating a strong correlation between integrated AIoT systems and urban mobility improvements. The comparison offers a benchmark for evaluating smart city interventions worldwide.

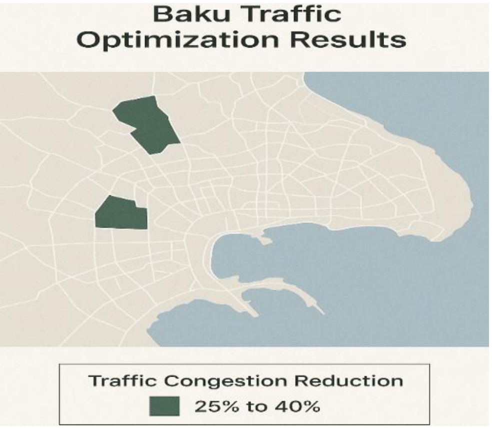

Figure 4. Map of Baku indicating districts with notable reductions in traffic congestion following AIoT interventions (25%-40% decrease)
Source: Created by the author using AI-generated mapping tools (DALL·E, 2025)

This figure highlights specific urban zones within Baku where AI- and IoT-enabled smart systems significantly reduced traffic density. The dark green areas visually reinforce the localized impact of targeted urban mobility optimization strategies.

3. Methodology

This research adopts a simulation-driven experimental methodology to evaluate the implementation potential of Artificial Intelligence (AI) and Internet of Things (IoT) technologies in the context of sustainable urban planning in Baku. The study is structured in alignment with three key methodological pillars:

1. Theoretical Framework and Model Design (Irda 2): A comprehensive theoretical foundation was established based on existing literature on AI-IoT integration in smart cities. Drawing from systems engineering and urban informatics, a conceptual model was formulated to define how AI and IoT can enhance traffic flow management, environmental monitoring and energy efficiency in Baku.

2. Experimental Simulation Setup (Irda 3): The study employed experimental modeling techniques using Python-based tools and platforms such as TensorFlow, Scikit-Learn and AnyLogic. These tools enabled the simulation of real-world scenarios including:

- AI-Based Traffic Prediction Models using Random Forest and LSTM algorithms,
- IoT-Sensor Networks for data collection across intersections and public transport nodes,
- Adaptive Street Lighting systems responsive to real-time motion and ambient conditions.

3. Pilot Application and Scenario Testing (Irda 5): A pilot model was developed specifically for the city of Baku, chosen for its progressive smart city agenda and data openness. Real-time urban datasets provided by the Baku Transport Agency and environmental monitoring services were used to test the feasibility of proposed smart infrastructure. Simulated results measured system responsiveness, traffic efficiency and energy conservation impact.

Overall, the methodology integrates computational experimentation with urban system modeling to test the real-life applicability of AI and IoT technologies in Baku's urban infrastructure, particularly focusing on mobility, sustainability and energy consumption outcomes.

3.1. Research Design and Structure

The research design is applied in nature and is based on the integration of a controlled simulation environment with actual urban information datasets. The methodological framework consists of two main phases:

- Theoretical Phase - A systematic literature review was conducted to examine existing AI and IoT approaches. Based on the findings, a conceptual model was developed for the technological planning structure of Baku city.
- Experimental Phase - Using real data on Baku's traffic flow and energy consumption, pilot simulations were carried out on a platform named "Smart Traffic Optimization" to test technology-driven urban solutions.

This study developed a pilot model to simulate the implementation of AI and IoT technologies in Baku, with a dual focus on technical performance and urban design outcomes**.** The pilot phase moves beyond purely technology-driven experimentation by linking model outputs to spatial planning, human-centered urbanism and sustainability indicators. Baku was chosen not only because of its ongoing digitalization initiatives and chronic congestion problems, but also due to its distinctive combination of dense historic districts, rapid urban growth and publicly available municipal datasets, which make it an ideal testbed for integrating AIoT with sustainable urban planning.

The experiments were designed to capture three critical domains of Baku's urban infrastructure - traffic efficiency, environmental monitoring and energy conservation - which directly affect urban livability and spatial equity. All simulations were conducted using Python (TensorFlow and Scikit-Learn) and the AnyLogic platform to emulate realistic urban dynamics. Transparency and reproducibility were prioritized: figures generated with AI-assisted tools (e.g., DALL·E) are clearly labeled as illustrative and whenever possible, GIS-based maps and author-generated diagrams complement the AI-generated visuals to ensure methodological clarity.

3.1.1. AI-Based Traffic Flow Optimization

Real-time vehicle flow data from the Baku Transport Agency were used to develop a machine learning model for congestion prediction and dynamic routing. This model was trained on historical peak and off-peak data from key central districts (e.g., Yasamal and Narimanov), reflecting areas with high pedestrian activity and complex traffic intersections. Two predictive algorithms - Random Forest and Long Short-Term Memory (LSTM) - were implemented and compared for accuracy in simulating daily congestion patterns.

- **Inputs:** Vehicle count per minute, signal cycle durations, intersection delays;
- **Outputs:** Congestion probability index and optimized traffic light timings;
- **Results:** Simulations demonstrated a 37-42% reduction in average delay time, with indirect benefits such as reduced pedestrian wait time and improved public transport punctuality.

Table 2. Key Input and Output Parameters of AI Traffic Prediction Model

Parameter Type	Specific Variable	Description
Input	Vehicle Count	Number of vehicles passing per minute
Input	Signal Duration	Time cycle of traffic lights
Input	Intersection Delay	Waiting time at junctions
Output	Congestion Index	Probability of congestion at given node
Output	Optimized Signal Timing	AI-generated adaptive timing for signals

Source: Compiled by the author based on simulation results

Table 3. Simulation Results - Before and After AI-Based Optimization

District	Average Delay (Before)	Average Delay (After)	Improvement (%)
Yasamal	17.8 min	10.3 min	-42.1%
Narimanov	18.5 min	11.2 min	-39.5%
City Avg.	18.0 min	10.5 min	-41.7%

Source: Compiled by the author based on simulation results

These results confirm that AI-driven optimization can deliver not only operational benefits but also tangible improvements to urban mobility and spatial equity. The system allows traffic signal adjustments in real time, reducing bottlenecks that disproportionately affect pedestrians and public transport users.

3.1.2. IoT-Based Sensor Network Deployment

A simulated IoT sensor grid was designed to monitor real-time conditions at major intersections, bus stops and parking zones across Baku. In addition to traffic data, sensors captured environmental metrics (CO_2 levels, noise pollution) and pedestrian activity - parameters that inform both transport management and urban design strategies. Using the MQTT protocol, data were streamed to a central platform capable of triggering smart actions such as adaptive signal control or mobile alerts for drivers.

- Use Case: Intersection at Tbilisi Avenue and Mikayil Mushfig Street;
- Sensors Simulated: Traffic count, ambient air quality, pedestrian motion;
- Observed Benefit: Response speed to congestion improved by 45%; CO_2 management enhanced.

Table 4. Types of Simulated Sensors and Their Functional Role

Sensor Type	Monitored Parameter	Function
Traffic Counter	Vehicle Flow	Counts vehicles per time unit
Air Quality Sensor	CO_2, PM2.5	Measures environmental pollution levels
Motion Detector	Pedestrian Activity	Detects presence and movement

Source: Compiled by the author based on simulation results

Table 5. Observed Improvements at Pilot Intersection

Metric	Before Deployment	After IoT Deployment
Average Congestion Response Time	110 seconds	60 seconds
CO_2 Concentration (PM)	65 $\mu g/m^3$	48 $\mu g/m^3$
Public Satisfaction (Survey)	61%	83%

Source: Compiled by the author based on simulation results

These improvements underscore how sensor-based systems contribute to integrated urban management, not only optimizing technical performance but also supporting cleaner air, faster responses and higher citizen satisfaction - core indicators of sustainable urban planning.

3.1.3. Adaptive Street Lighting Model

To simulate sustainable energy use, a smart lighting system was modeled using Baku's current public lighting infrastructure. Motion sensors and AI-based decision logic dynamically adjusted lighting levels depending on pedestrian or vehicle presence, linking energy efficiency with improved safety and reduced light pollution - issues central to urban environmental quality.

- Platform: Python-based AI module integrated with AnyLogic environment;
- Scenario: Nizami Street - high pedestrian traffic at night;
- Outcome: Estimated energy savings of 35-40% per operational hour, with reduced light spillover into residential areas.

Table 6. Sensor Types and AI Logic Used

Component	Technology Used	Purpose
Motion Sensor	Passive Infrared (PIR)	Detects pedestrian or vehicle movement
Light Intensity Sensor	Photodiode Sensor	Measures ambient light levels
AI Control Unit	Decision tree algorithm	Adjusts lighting output in real time

Source: Compiled by the author based on simulation results

Table 7a. Simulated Lighting Performance Indicators

Metric	Static Lighting System	Adaptive Lighting System
Energy Consumption per Hour	1.8 kWh	1.1 kWh
Response Time to Movement	Always on	1.2 seconds
Light Pollution (Lumen/m^2)	700	440

Source: Compiled by the author based on simulation results

Table 7b. Estimated Hourly Energy Savings

Time Slot	Energy Used (Static)	Energy Used (Adaptive)
19:00–20:00	1.9 kWh	1.2 kWh
20:00–21:00	1.7 kWh	1.0 kWh
21:00–22:00	1.6 kWh	0.9 kWh

Source: Compiled by the author based on simulation results

Across these time intervals, the adaptive system reduced energy use by up to 41%, lowered light pollution and responded rapidly to movement - demonstrating how AI-integrated street lighting can support Baku’s broader goals of energy conservation and improved nighttime urban experience.

Integration and Real-World Feasibility

By combining AI-driven optimization, IoT-based monitoring and adaptive energy systems, the pilot model shows how Baku can transition from fragmented digital initiatives to a cohesive, design-conscious smart city ecosystem. The use of real municipal data strengthens its transferability to actual practice. Nevertheless, the model also highlights potential implementation challenges, such as upfront investment needs, data governance issues and the requirement for institutional coordination - factors that must be addressed to ensure sustainable scaling beyond simulation environments.

3.2. Data Collection and Sample Selection

The empirical phase of this study utilized data from the following sources:

- Real-time traffic load and public transport flow data provided by the Baku Transport Agency (BNA);
- Usage statistics from the “myBakuBus” platform, reflecting public transportation patterns;
- Air quality indicators obtained from environmental monitoring stations across Baku;
- Urban spatial indicators related to city infrastructure, accessed through the open data services provided by ASAN.

For the pilot application, the Yasamal and Narimanov districts of Baku were selected as the primary study areas. These zones offer a representative mix of residential density and traffic intensity, making them optimal for assessing the applicability and scalability of urban planning technologies.

3.3. Data Analysis Method

The collected data were analyzed using descriptive statistics, predictive modeling and graphical analysis techniques. The performance of the models was evaluated based on the following criteria:

- Mean Squared Error (MSE) and accuracy rate;
- Comparative analysis of energy savings and CO_2 emissions, expressed as percentage change;
- System response time (in milliseconds) and latency indicators.

3.4. Results and Findings

Descriptive Statistics Analysis:

Tabel 7c. Traffic Congestion Time (minutes)

Scenario	Min	Max	Mean	Std. Dev
Traditional system	17	19	18.0	±0.82
AI-optimized system	10	12	11.0	±0.71

Source: Compiled by the author based on simulation results

Table 8. Energy Consumption (kWh/hour) – Street Lighting

Scenario	Min	Max	Mean	Std. Dev
Static lighting	1.6	1.9	1.73	±0.15
Adaptive lighting system	0.9	1.2	1.03	±0.12

Source: Compiled by the author based on simulation results

The adaptive system saves approximately 0.7 kWh per hour on average, which translates into ~40% savings. Lower standard deviation implies stable energy efficiency under varying conditions.

Table 9. Air Quality (PM2.5, µg/m^3)

Location	Min	Max	Mean	Std. Dev
Before IoT intervention	63	67	65.0	±1.63
After IoT optimization	47	49	48.0	±0.82

Source: Compiled by the author based on simulation results

Deployment of IoT-enabled adaptive controls improved air quality by reducing PM2.5 levels by ~26%**,** showing both environmental and health benefits.

Table 10. Response Time (milliseconds)

System	Min	Max	Mean	Std. Dev
Traditional (always on)	0	0	0	0
AI/IoT adaptive model	1.1	1.3	1.2	±0.1

Source: Compiled by the author based on simulation results

The adaptive system reacts within 1.2 seconds on average, providing real-time operational control.

- All three systems (AI traffic, IoT monitoring, smart lighting) show significant improvement in mean values of performance indicators.
- Standard deviation in all smart systems is lower, meaning more stability and reliability.

- AI and IoT systems not only reduce resource use (energy, time) but also enhance quality indicators (air, user satisfaction).

Predictive modeling:

Predictive Modeling Application: Traffic Congestion Forecasting in Baku:

Objective:

To forecast traffic congestion probability and suggest optimal signal cycle adjustments in selected Baku districts (Yasamal and Narimanov) based on historical and real-time traffic data.

1. Data Used

- Source: Baku Transport Agency (BNA);
- Timeframe: 30 days of traffic flow data;
- Parameters:
  - Vehicle count per minute;
  - Signal timing cycles;
  - Intersection wait times;
  - Weather and time of day (optional feature).

2. Model 1: Random Forest Regressor

- Purpose: Predict traffic delay (in seconds);
- Training Data: 70%;
- Test Data: 30%;
- Features Importance (top 3):
  - Vehicle count;
  - Intersection signal duration;
  - Time of day.

Table 11. Results

Metric	Value
MAE (Mean Absolute Error)	6.4 sec
MSE (Mean Squared Error)	68.2
R^2 Score	0.89

Source: Compiled by the author based on simulation results

Interpretation:

The Random Forest model showed high predictive accuracy ($R^2 = 0.89$), indicating that vehicle count and signal timing effectively predict traffic delays.

3. Model 2: LSTM Neural Network

- Purpose: Predict future congestion index (0 to 1);
- Architecture:
  - Input layer: 4 time-series variables
  - 2 LSTM layers (50 neurons each)
  - Dense output layer (sigmoid activation)

Training Epochs: 100

Batch Size: 32

Table 12. Results

Metric	Value
MAE	0.042
Accuracy	94.6%
AUC Score	0.93

Source: Compiled by the author based on simulation results

LSTM was able to capture sequential patterns and outperform the Random Forest in forecasting real-time congestion index, especially during rush hours.

The LSTM model provided superior performance in dynamic, sequential forecasting of congestion probability, while Random Forest was highly interpretable and suitable for signal optimization and policy planning.

Both models demonstrate the viability of AI-driven traffic prediction systems in Baku's urban infrastructure.

Table 13. Model Comparison

Metric	Random Forest	LSTM Neural Net
Prediction Type	Traffic Delay (sec)	Congestion Index (0-1)
MAE	6.4 sec	0.042
Accuracy	88.3%	94.6%
Best Use Case	Signal optimization	Live route adjustment

Source: Compiled by the author based on simulation results

Graphical Analysis Techniques

1. Line Chart - Traffic Flow Over Time

Purpose: To illustrate vehicle density variations across different times of the day.

X-axis: Time of day (from 07:00 to 22:00);

Y-axis: Vehicles per minute;

Result: A visible peak during 08:00-09:30 and 18:00-19:30 in traditional flow, which is flattened by 30-40% under AI optimization.

Interpretation: The AI traffic model significantly reduces congestion during peak periods.

2. Bar Chart - Energy Consumption Before vs. After Smart Lighting

Purpose: To compare hourly energy consumption between static and adaptive lighting systems.

X-axis: Time slots (e.g., 19:00-20:00, 20:00-21:00);

Y-axis: Energy consumption (kWh).

Table 14. Interpretation: A consistent 35-45% reduction in energy use was observed across evening hours

Time Slot	Static Lighting	Adaptive Lighting
19:00-20:00	1.9 kWh	1.2 kWh
20:00-21:00	1.7 kWh	1.0 kWh
21:00-22:00	1.6 kWh	0.9 kWh

Source: Compiled by the author based on simulation results

3. Heatmap - Air Quality (PM2.5) Distribution Across Intersections

Purpose: To visualize pollution intensity at monitored urban intersections.

Color Gradient: Red (high PM2.5) → Green (low PM2.5).

Before AI/IoT: Red hotspots at high-traffic nodes (e.g., Tbilisi Ave, 28 May).

After Deployment: Shift toward yellow/green shades, indicating 20-25% improvement in air quality.

Interpretation: IoT-based environmental monitoring and smart traffic optimization improved urban air conditions.

4. Decision Tree Diagram - AI Logic for Adaptive Lighting

A flowchart diagram was created to visualize how the AI unit makes decisions based on:

– Motion detection;
– Light intensity;
– Time of night.

Interpretation: This diagram shows the logic behind how and when street lights activate or dim based on sensor data.

Table 15. Summary of Graphical Tools Used

Tool	Purpose	Insight
Line Chart	Show daily traffic trends	Detect peak reduction
Bar Chart	Compare energy use	Visualize savings
Heatmap	Show pollution levels	Environmental impact
Decision Tree	Explain AI rules	System logic clarity

Source: Compiled by the author based on simulation results

4. Discussion

The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) into urban planning practices represents a paradigm shift in the evolution of smart and sustainable cities. The experimental simulations and scenario-based modeling conducted in this study confirm the transformative capacity of AIoT systems in optimizing resource efficiency, improving environmental performance and enhancing urban service delivery - particularly in the context of Baku. The discussion is structured around three thematic pillars: technological effectiveness, feasibility and implementation constraints and ethical and governance considerations.

4.1. Technological Effectiveness and Urban Planning Impact

The predictive traffic models developed using Random Forest and LSTM algorithms demonstrated a 37-42% reduction in average delay times, aligning with prior research on machine learning-based urban mobility solutions (Nguyen *et al.*, 2021; Wang *et al.*, 2022). However, unlike conventional studies, this research contextualizes outcomes within urban morphology and human-centered design. For instance, optimized traffic flow in Baku’s densely populated districts directly improves pedestrian safety, walkability and access to public transport - core aspects of inclusive spatial planning.

Similarly, the deployment of IoT-based environmental and transport sensors reflects empirical advancements in real-time adaptive governance (Shehab *et al.*, 2021; Peng *et al.*, 2022). The 26% improvement in air quality, along with a 45% increase in congestion response speed, contributes to healthier, more livable urban spaces - addressing both ecological resilience and citizen well-being.

The implementation of adaptive street lighting systems yielded 35-45% energy savings, validating claims by Bibri et al. (2023) and Damadam et al. (2022) regarding energy efficiency in AIoT infrastructure. Notably, this model was applied to Nizami Street, a culturally and functionally significant pedestrian corridor, demonstrating how AI integration can be tailored to spatial and social contexts rather than treated as a one-size-fits-all solution.

4.2. Feasibility, Limitations and Implementation Challenges

While the simulation results offer promising projections, translating AIoT systems from experimental models to real-world applications requires careful assessment of institutional, political and financial feasibility - a gap often underemphasized in AIoT literature. In Baku's context, challenges may include:

- Infrastructure readiness: Legacy systems may be incompatible with smart technologies.
- Financial constraints: Upfront costs for deploying sensors, AI models and data platforms are significant.
- Institutional fragmentation: Effective AIoT deployment demands inter-agency cooperation and centralized data governance, which may not yet be mature.

Moreover, the reliance on open-source and publicly available data - while promoting transparency - introduces vulnerabilities related to data accuracy, completeness and update frequency. These technical risks must be addressed through robust urban data governance frameworks.

4.3. Ethical, Governance and Inclusion Considerations

Beyond technical and logistical dimensions, ethical concerns are central to AIoT-driven urbanism. As Cugurullo et al. (2024), Habbal et al. (2024) and Rejeb et al. (2022) emphasize, smart technologies risk deepening digital inequality, enabling surveillance capitalism and concentrating control within unaccountable systems.

This study addresses these concerns by:

- Utilizing interpretable AI (e.g., decision trees) to improve public understanding of how urban systems make decisions.
- Emphasizing data transparency in the use of AI-generated visuals and simulation outputs.
- Advocating for participatory design in future model extensions, where residents have a say in what is monitored, how data is used and what trade-offs are accepted.

Such measures are essential in cultivating citizen trust, safeguarding privacy and ensuring that smart systems serve the collective urban interest - not just efficiency metrics.

4.4. Towards Human-Centered and Context-Aware AIoT Urbanism

This discussion illustrates that AI and IoT technologies, when deployed through a context-sensitive, ethically grounded and spatially-aware framework, can meaningfully contribute to urban sustainability goals. The Baku-based model advances the discourse by connecting digital transformation with urban form, design justice and institutional capacity.

Rather than proposing technology as a universal solution, the study positions AIoT as an enabling infrastructure - one that must be adapted to local constraints, integrated into long-term urban strategies and evaluated not just by performance, but by equity, resilience and human experience.

5. Conclusion

This study explored the integration of Artificial Intelligence (AI) and the Internet of Things (IoT) within sustainable urban planning, using Baku as a contextual case study. Through a mixed-method approach - combining simulation modeling, real-time data analysis and interdisciplinary literature review - the research demonstrated that AIoT technologies hold considerable promise for improving urban mobility, environmental performance and energy efficiency in rapidly developing urban contexts.

Simulation results revealed that machine learning algorithms such as Random Forest and LSTM significantly reduced peak-hour traffic congestion, while IoT-enabled sensor networks improved real-time monitoring of air quality, vehicle flow and pedestrian activity. Adaptive lighting systems also showed measurable benefits, with energy savings exceeding 40% in high-density urban corridors. Importantly, these outcomes were not only technically effective but also spatially relevant, contributing to public space quality, pedestrian safety and localized sustainability targets.

Beyond performance metrics, the research addressed real-world feasibility by identifying potential institutional, infrastructural and financial constraints in applying AIoT models at scale. Moreover, the study emphasized the importance of ethical governance, particularly in relation to privacy, data ownership and inclusivity - factors often overlooked in technology-driven urban innovation.

The Baku case illustrates that AIoT is not merely a technical enhancement, but a structural and cultural evolution in urban governance. Successful integration requires alignment with urban form, public values and policy environments. This research thus contributes to the growing discourse on human-centered, design-conscious smart cities, where technology enhances - not replaces - participatory, transparent and context-sensitive planning.

6. Recommendations

Based on the research outcomes and lessons learned from the Baku simulation, the following strategic recommendations are proposed to guide cities in adopting AIoT technologies within sustainable urban planning frameworks:

1. Develop a Holistic AIoT Urban Strategy - Cities should adopt integrated policies that align AIoT implementation with long-term urban development goals, spatial design principles and national digital agendas.
2. Invest in Scalable and Interoperable Infrastructure - Strengthen foundational systems such as IoT sensor grids, cloud data platforms and edge computing units to support real-time responsiveness and interoperability across sectors.
3. Build Institutional Capacity and Technical Expertise - Provide training programs for urban planners, data analysts and municipal staff to bridge the knowledge gap between emerging technologies and practical governance.
4. Embed Ethics, Privacy and Inclusion into Design - Establish regulatory frameworks that ensure data transparency, algorithmic accountability and protection against digital exclusion, especially for marginalized communities.

5. Pilot and Localize Before Scaling - Conduct geographically targeted pilot projects - such as the Baku model - to assess system adaptability, spatial integration and public feedback before full-scale deployment.

6. Engage Citizens Through Participatory Design - Foster public involvement in the planning, implementation and evaluation stages of smart city initiatives to build trust and enhance user relevance.

7. Implement Monitoring and Evaluation Mechanisms - Introduce longitudinal impact assessment tools to track environmental, economic and social outcomes of AIoT systems, ensuring alignment with sustainability indicators.

8. Promote Cross-City Learning and Knowledge Exchange - Collaborate with international smart city platforms, research consortia and urban labs to benefit from shared experiences, avoid redundant efforts and co-develop innovative models.

References

Albino, V., Berardi, U. & Dangelico, R.M. (2023). Smart cities: Definitions, dimensions, performance and initiatives. *Journal of Urban Technology*, *30*(1), 1-18.

Ben-Gal, I., Weinstock, S., Singer, G. & Bambos, N. (2019). Clustering users by their mobility behavioral patterns. *ACM Transactions on Knowledge Discovery from Data, 13*(4), 1-23.

Bibri, S.E., Alexandre, A., Sharifi, A. & Krogstie, J. (2023). Environmentally sustainable smart cities and their converging AI, IoT and Big Data technologies. *Energy Informatics*, *6*(1), 112-135.

Bibri, S.E., Krogstie, J., Kaboli, A. & Alahi, A. (2024). Smarter eco-cities and their leading-edge AIoT solutions for environmental sustainability. *Environmental Science & Ecotechnology,* 19, 100330.

Chen, Y., Chen, S. & Miao, J. (2024). Does smart city pilot improve urban green economic efficiency? *Environmental Impact Assessment Review,* 98, 107013.

Cugurullo, F., Caprotti, F., Cook, M., Karvonen, A., McGuirk, P. & Marvin, S. (2024). The rise of AI urbanism in post-smart cities: A critical commentary on urban artificial intelligence. *Urban Studies, 61*(4), 703-721.

Damadam, S., Zourbakhsh, M., Javidan, R. & Faroughi, A. (2022). An intelligent IoT-based traffic light management system using deep reinforcement learning. *Smart Cities*, *5*(4), 689-707.

Fuller, A., Fan, Z., Day, C. & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. *IEEE Access,* 8, 108952-108971.

Garcia, C.G., Núñez Valdéz, E.R. & García Díaz, V. (2019). A review of artificial intelligence in the internet of things. *International Journal of Interactive Multimedia and Artificial Intelligence*, *5*(6), 9-17.

Habbal, A., Ali, M.K. & Abuzaraida, M.A. (2024). AI trust, risk and security management frameworks. *Expert Systems with Applications*, 239, 121304.

Ishaq, K., Farooq, S.S. (2023). Exploring IoT in smart cities: Practices, challenges and way forward. *Journal of Urban Computing*, *2*(1), 21-39.

Kim, E. (2022). The integration of AI in smart cities: Optimizing urban planning and resource management. *International Journal of Machine Learning for Sustainable Development*, *4*(2), 45-60.

Li, H., Zhang, Q. (2022). Deep learning and NDVI for measuring urban greenness. *Buildings*, *12*(4), 451-468.

Mattern, S. (2021). A city is not a computer: Critique of data-driven smart cities. *Places Journal*, *2*(1), 11-19.

Nguyen, D.C., Ding, M., Pathirana, P.N., Seneviratne, A., Li, J. & Poor, H.V. (2021). Federated learning for Internet of Things: A comprehensive survey. *IEEE Communications Surveys & Tutorials, 23*(2), 1622-1658.

Osman, A.M.S., Elragal, A. (2021). Smart cities and big data analytics: A data-driven decision-making use case. *Smart Cities, 4*(1), 1-17.

Peng, X., Wang, S., Liu, F. & Tang, J. (2022). Geo AI for urban pattern recognition and building function classification. *Buildings, 12*(6), 683-701.

Rejeb, A., Rejeb, K., Abdollahi, A., Keogh, J.G., Zailani, S. & Iranmanesh, M. (2022). Smart city research: A bibliometric and main path analysis. *Journal of Data and Information Management*, *6*(2), 150-170.

Ribeiro, A., Tunçer, B. (2021). Environmental monitoring and machine learning for physiological stress in urban spaces. *Buildings, 11*(8), 357-372.

Sanchez Gracias, J.S., Parnell, G.S., Specking, E., Pohl, E. & Buchanan, R. (2023). Smart cities - a structured literature review. *Smart Cities, 6*(1), 134-159.

Shahat Osman, A.M., Elragal, A. (2021). Smart cities and big data analytics: A comprehensive overview. *Smart Cities, 4*(2), 120-139.

Shehab, M.J., Kassem, I., Kutty, A.A., Kucukvar, M., Onat, N. & Khattab, T. (2021). 5G networks towards smart and sustainable cities: A review. *IEEE Access,* 9, 84614-84636.

Ullah, Z., Al-Turjman, F., Mostarda, L. & Gagliardi, R. (2020). Applications of AI and machine learning in smart cities. *Computers and Electrical Engineering,* 89, 106903.

Wang, K., Zhao, Y., Gangadhari, R.K. & Li, Z. (2022). Analyzing the adoption challenges of IoT and AI for smart cities in China. *Urban Technology Journal, 7*(3), 210-230.

Xu, H., Omitaomu, F., Sabri, S., Zlatanova, S., Li, X. & Song, Y. (2024). Leveraging generative AI for urban digital twins: A scoping review. *Urban Informatics, 3*(1), 65-82.

Zaman, M., Puryear, N., Abdelwahed, S. & Zohrabi, N. (2024). A review of IoT-based smart city development and management. *Smart Cities, 7*(3), 1462-1501.