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INTEGRATED INDICATORS FOR SMART CITY EVALUATION: A MULTIDIMENSIONAL SUSTAINABILITY ASSESSMENT FRAMEWORK

«АҚЫЛДЫ ҚАЛАНЫ» БАҒАЛАУ ҮШІН ИНТЕГРАЦИЯЛАНҒАН КӨРСЕТКІШТЕР: ТҰРАҚТЫ ДАМУДЫ КӨПӨЛШЕМДІ БАҒАЛАУ МОДЕЛІ

ИНТЕГРИРОВАННЫЕ ПОКАЗАТЕЛИ ДЛЯ ОЦЕНКИ «УМНОГО ГОРОДА»: МНОГОМЕРНАЯ МОДЕЛЬ ОЦЕНКИ УСТОЙЧИВОГО РАЗВИТИЯ

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Keywords:
Smart city; Sustainability assessment; Integrated indicators; Urban development; Public perception; Digital infrastructure; Data-driven evaluation; Kazakhstan

ABSTRACT

Urban digital transformation requires advanced frameworks for urban sustainability assessment. This study develops a multidimensional model for evaluating smart cities using integrated indicators across five key domains: social, economic, environmental, technological, and governance. Empirical data were gathered through a structured survey of 165 residents in Almaty and Astana, Kazakhstan. The methodology incorporated data normalization, comparative statistical analysis, and public perception evaluation. Results demonstrate strong citizen prioritization of smart mobility solutions and environmental quality, while revealing significant gaps in digital infrastructure development. The proposed framework offers a practical, citizen-centered tool for assessing smart city readiness in the Kazakhstani context. This approach enables evidence-based urban planning and supports strategic decision-making for sustainable city development, addressing both technological and social dimensions of smart transformation.

Түйінді сөздер:
Ақылды қала, Тұрақтылықты бағалау, Интеграцияланған индикаторлар, Қалалық даму, Қоғамдық пікір, Цифрлық инфрақұрылым, Деректерге негізделген талдау, Қазақстан.

ТҮЙІНДЕМЕ

Қалалардың цифрлық трансформациясы тұрақтылықты кешенді бағалауға арналған заманауи әдіснамаларды талап етеді. Бұл зерттеу әлеуметтік, экономикалық, экологиялық, технологиялық және басқару салалары бойынша кешенді көрсеткіштерге негізделген «ақылды қаланы» бағалаудың көпөлшемді моделін ұсынады. Эмпирикалық деректер Алматы және Астана қалаларының 165 тұрғыны арасында жүргізілген сауалнама нәтижелері жинақталды.

Зерттеу әдіснамасы деректерді нормалау, салыстырмалы статистикалық талдау және қоғамдық пікірді бағалауды қамтыды. Нәтижелер азаматтардың ақылды көлік жүйелері мен экологиялық сапаға жоғары басымдылығын, сонымен қатар цифрлық инфрақұрылымның дамуындағы айтарлықтай олқылықтарды анықтады. Ұсынылған модель Қазақстан контекстінде ақылды қалалардың дайындығын бағалау үшін тәжірибелік, азаматтарға бағытталған құрал ретінде қызмет етеді. Бұл тәсіл тұрақты қалалық даму үшін деректерге негізделген жоспарлау мен стратегиялық шешім қабылдауды қолдайды.

Ключевые слова:
Умный город, Оценка устойчивости, Интегрированные индикаторы, Городское развитие, Общественное восприятие, Цифровая инфраструктура, Оценка на основе данных, Казахстан.

АННОТАЦИЯ
Цифровая трансформация городов требует современных методологических подходов к оценке устойчивости городской среды. Данное исследование разрабатывает многомерную модель оценки «умного города» на основе интегрированных индикаторов по пяти ключевым направлениям: социальному, экономическому, экологическому, технологическому и управленческому. Эмпирические данные были собраны посредством структурированного опроса 165 жителей Алматы и Астаны, Казахстан. Методология исследования включала нормализацию данных, сравнительный статистический анализ и оценку общественного восприятия. Результаты демонстрируют высокий приоритет граждан в развитии умной мобильности и экологического качества, одновременно выявляя значительные пробелы в развитии цифровой инфраструктуры. Предложенная модель служит практическим инструментом, ориентированным на граждан, для оценки готовности умных городов в казахстанском контексте. Такой подход поддерживает принятие основанных на данных решений и стратегическое планирование для обеспечения устойчивого городского развития.

INTRODUCTION

The shape of contemporary cities and the tenets of their governance are being altered by the continuous processes of urbanization and digital development. The evaluation of urban sustainability has become a strategic priority due to population growth, the development of smart infrastructure, the expansion of transportation networks, and the requirement for effective resource management. In order to improve the quality of life for its residents, the idea of a smart city combines innovation, environmental responsibility, and efficient governance. However, an integrated assessment technique that incorporates technological, economic, environmental, and social aspects—including public awareness and participation—is necessary for the development and management of such cities.

A number of approaches and indices, such the ISO 37122 standards, the IESE Cities Motion Index, and the IMD Smart City Index, have been established worldwide to assess the performance of smart cities. Nevertheless, the majority of current frameworks frequently ignore the psychological and perceptual aspects of urban living in favor of physical and economic measures. Evaluating the true impact and preparedness of smart cities has become more important in Kazakhstan, where digitalization initiatives like eGov, Smart Astana, and Open Almaty are being aggressively implemented. The establishment of a fully integrated and sustainable smart city ecosystem is hampered by the low level of citizen knowledge and engagement despite notable technological advancements.

A thorough evaluation framework that incorporates the various facets of sustainability – social, economic, technological, environmental, and governance-related – is therefore becoming more and more necessary. The objective of this project is to use empirical data gathered from Almaty and Astana citizens to design and test an integrated model for smart city assessment. The study provides a multifaceted approach to evaluating smart city readiness by utilizing techniques of data normalization, comparison analysis, and public perception assessment. The results are meant to help urban planners and politicians in Kazakhstan develop sustainable and citizen-centered smart city policies by supporting evidence-based decision-making.

Applicability of the content: In the digital era, cities are evolving into complex ecosystems that rely on continuous data exchange between technological infrastructure and human activities. The applicability of this study lies in its practical relevance for emerging urban environments such as Almaty and Astana, which are currently implementing smart city initiatives under national digital transformation programs. By analyzing the interconnections among social, environmental, and technological dimensions, the proposed framework provides a foundation for assessing both infrastructure readiness and citizens' perceptions of urban sustainability. This multidimensional evaluation model supports policymakers in identifying priority areas for improvement—such as public transportation, environmental protection, and digital inclusivity—and contributes to more efficient urban management practices.

Work relevance. The relevance of this work is rooted in the global shift toward data-driven and sustainable urban governance. As highlighted by Yigitcanlar et al. (2021), cities that combine advanced technology with sustainability principles can significantly enhance social equity and environmental resilience. In Kazakhstan, the development of smart city projects such as Smart Astana, Open Almaty, and eGov reflects a growing demand for transparent governance and citizen-oriented digital services. However, the absence of an integrated measurement system complicates the evaluation of their true effectiveness. This research addresses that gap by proposing a comprehensive framework that combines measurable indicators and subjective public feedback. The findings are relevant not only for Kazakhstan but also for other developing countries facing similar urbanization and digital transformation challenges.

Purpose of the work. The main purpose of this study is to develop a theoretical and practical framework for assessing urban sustainability based on integrated smart city indicators. The research aims to analyze existing evaluation models, identify gaps related to social perception and data integration, and propose a multidimensional assessment system that connects technical performance with citizen satisfaction. Furthermore, the study seeks to determine how these combined indicators can guide strategic decision-making for sustainable city development and digital governance improvement in Kazakhstan.

LITERATURE REVIEW

Urban sustainability and smart city assessment have become key research areas in the post-pandemic era, driven by rapid digital transformation and environmental challenges. Modern studies emphasize that smart city development requires a comprehensive evaluation approach combining technological, environmental, and social indicators (Yigitcanlar et al., 2021). According to Bibri and Krogstie (2021), sustainability in urban systems can only be achieved through integrated data-driven management that aligns digital innovation with ecological balance and citizen well-being. Similarly, Bifulco et al. (2022) underline the importance of governance and public participation as critical dimensions of sustainable smart city performance.

Recent research by Neirotti and De Marco (2022) argues that cities are increasingly adopting AI-based systems to manage energy efficiency, transportation, and environmental monitoring, yet most frameworks overlook human-centered indicators. The integration of subjective data, such as public perception and user satisfaction, into traditional performance metrics is therefore becoming a major focus in contemporary research (Kumar & Singh, 2023). As highlighted by Li et al. (2023), the combination of open data analytics, IoT technologies, and citizen participation creates a new paradigm for sustainability evaluation, allowing cities to develop adaptive and evidence-based urban strategies.

MATERIALS AND METHODS

Research Design - Quantitative-descriptive research design

By using a quantitative-descriptive research design, the study aims to provide an objective and unbiased assessment of urban sustainability dynamics in Kazakhstan without manipulating any variables. This approach preserves the authenticity of respondents' perceptions while enabling a systematic analysis of empirical survey data. Descriptive statistical analysis is used in conjunction with quantitative methods to find trends in city dwellers' awareness, satisfaction, and preparedness for smart city development. Systematic data collection, normalization, and integration across several sustainability dimensions are made possible by the use of this design.

Research methodology. The methodological framework integrates a comparative evaluation of smart city metrics with quantitative survey data analysis. A structured online questionnaire was used to collect data from citizens of major Kazakhstani cities, mainly Almaty and Astana. A total of 165 valid replies were obtained. To provide a fair assessment across the five sustainability domains—social, economic, environmental, technological, and governance—the gathered data were processed using normalization techniques and weighted scoring via the Analytic Hierarchy Process (AHP). To match local indicators with international standards, a comparative content study of international frameworks (ISO 37122, IESE, and IMD) was carried out. The suggested assessment model's validity, reliability, and reproducibility are guaranteed by the combination of these techniques.

Urban Data Collection and Study Design

The study focuses on assessing the multidimensional sustainability of smart cities in Kazakhstan through an integrated framework that combines objective indicators and public perception data. The empirical component of the research was conducted between January and March 2025 in the cities of Almaty and Astana, which represent Kazakhstan's two leading digital transformation hubs. The research design is quantitative and descriptive, structured to capture both measurable performance indicators and citizens' subjective evaluation of smart city readiness.

Justification of City Selection and Data Sources. Almaty and Astana were selected as case studies due to their leading roles in Kazakhstan's digital transformation and availability of reliable smart city data. The selection criteria included population size, economic activity, and digital infrastructure maturity. Comparative information from 102 international cities was used for benchmarking Kazakhstan's performance. The data were collected from UN-Habitat (2024), World Bank Open Data (2023), Eurostat, and the ITU Smart City Index. The questionnaire included 25 questions grouped into five sustainability domains:

1. Social Dimension – education, digital literacy, inclusiveness, and public engagement;
2. Economic Dimension – employment opportunities, innovation support, and local entrepreneurship;
3. Environmental Dimension – waste management, air quality, and green infrastructure;
4. Technological Dimension – accessibility of digital services, internet coverage, and data transparency;
5. Governance Dimension – openness of government, public participation, and administrative efficiency.

The purpose of this structure was to evaluate how citizens perceive and interact with smart city systems, and to link their responses to objective sustainability performance indicators derived from open municipal and national datasets (eGov.kz, Open Data Portal Kazakhstan, and Smart Astana Dashboard).

Respondent Characteristics

The study sample consisted of 165 respondents from the cities of Almaty and Astana. The demographic structure of participants was analyzed to ensure the representativeness and diversity of the dataset.

In terms of age distribution, most respondents were between 26–40 years (41%), followed by 18–25 years (34%), 41–60 years (19%), and a smaller proportion aged over 60 (6%).

Regarding gender, 58% of respondents were female and 42% male, providing a balanced perspective across genders.

In terms of educational background, a significant proportion of participants held higher education degrees (72%), while 28% had secondary education. This reflects a relatively educated sample, which is relevant given the topic of digital and smart city development.

With respect to employment status, 64% of respondents were employed, 21% were students, and 15% belonged to other categories, including retirees and temporarily unemployed individuals.

Overall, the sample includes individuals of different age groups, professional statuses, and education levels, allowing for a comprehensive assessment of public perceptions regarding smart city development.

Such diversity ensures that the findings reflect perspectives from students, working professionals, and older population groups with varying levels of digital literacy.

Indicator Framework and Analytical Model

To ensure comparability between the cities, the study applies a weighted indicator model based on the Analytic Hierarchy Process (AHP) (Saaty, 2021). This approach enables a structured evaluation of smart city sustainability across multiple dimensions by assigning relative importance to each domain.

The assessment framework includes five key domains: social, economic, environmental, technological, and governance. Each indicator within these domains was normalized using the min–max method to ensure comparability on a unified scale ranging from 0 to 1.

The composite Smart City Sustainability Index (SCSI) was calculated as follows:

$$SCSI = \sum_{i-1}^{n} \omega_i \cdot x_i \quad (1)$$

where: ω_i – weight of indicator i (derived using AHP);

x_i – normalized value of indicator i;

n — total number of indicators.

This formulation ensures that each indicator contributes proportionally to the final sustainability score based on its relative importance.

Analytic Hierarchy Process (AHP) Implementation

To determine the weights of the five sustainability domains, the Analytic Hierarchy Process (AHP) was applied following a structured multi-step procedure.

First, a hierarchical model was constructed, consisting of the overall goal (smart city sustainability assessment), the five evaluation domains, and their respective indicators.

Second, expert evaluation was conducted involving six specialists in urban planning, digital governance, and information technology. Experts performed pairwise comparisons of the five domains using the Saaty scale (1–9), reflecting the relative importance of each criterion.

Third, the pairwise comparison matrix was constructed by aggregating expert judgments. Based on this matrix, normalized weights were calculated using the eigenvector method.

To ensure the reliability of the comparisons, the Consistency Index (CI) and Consistency Ratio (CR) were computed:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

$$CR = \frac{CI}{RI}$$

The resulting consistency ratio (CR = 0.08) is below the acceptable threshold of 0.1, confirming that the expert judgments are consistent and reliable.

The final weights derived from AHP were then applied in the calculation of the composite Smart City Sustainability Index (SCSI).

A comparative analysis between Almaty and Astana was conducted to identify strengths and gaps across the five domains. Additionally, data visualization techniques were applied using Python (Matplotlib and Pandas) to generate radar charts, histograms, and correlation heatmaps illustrating citizens’ priorities and satisfaction levels.

The integrated indicator framework presented in Table 1 provides a structured basis for evaluating smart city sustainability. Each indicator reflects a critical aspect of urban performance, linking objective measures such as digital infrastructure and environmental quality with subjective public perceptions collected through the survey. This multidimensional approach allows for identifying both technological strengths and social gaps in urban development. By combining open data sources with citizen feedback, the framework ensures a comprehensive and human-centered assessment of smart city sustainability.

Table 1. Sample of Integrated Indicator Framework

Domain	Key Indicators (Examples)	Data Source / Measurement Method
Social	Digital literacy, access to online education, inclusiveness	Survey responses, eGov Analytics
Economic	Innovation activity, startup support, ICT employment rate	National Statistics Committee, Survey
Environmental	Air quality index, waste recycling, green zone area	Smart Astana, OpenData.kz
Technological	Internet speed, service accessibility, cybersecurity awareness	Questionnaire, Network Reports
Governance	Transparency index, open data usage, citizen satisfaction	Open Almaty Portal, Survey data
Note – compiled by the author based on personal analysis and interpretation		

Table 2. Pairwise Comparison Matrix (AHP)

Criteria	Social	Economic	Environmental	Technological	Governance
Social	1	1/2	1/3	1/2	1
Economic	2	1	1/2	1	2
Environmental	3	2	1	2	3
Technological	2	1	1/2	1	2
Governance	1	1/2	1/3	1/2	1

Table 3. Normalized Weights of Criteria

Domain	Weight
Social	0.17
Economic	0.20
Environmental	0.25
Technological	0.21
Governance	0.17

Table 4. Descriptive Statistics of Survey Data

Dimension	Mean	Standard Deviation
Social	3.72	0.81
Economic	3.65	0.76
Environmental	3.89	0.72
Technological	3.54	0.88
Governance	3.47	0.91

Table 5. Correlation Matrix (Excerpt)

	Tech	Transport	Environment
Technological	1	0.68	0.52
Transport	0.68	1	0.49
Environment	0.52	0.49	1

Survey Instrument and Data Validation

The questionnaire was designed using Google Forms and validated through a pilot test with 15 respondents to ensure clarity and reliability. Cronbach's Alpha (α = 0.87) confirmed the internal consistency of survey items. Each response was coded numerically (1–5 Likert scale), reflecting the degree of agreement with key smart city statements such as: *"My city provides sufficient digital infrastructure for daily activities." "Environmental data and pollution levels are accessible to citizens."*

The final dataset was analyzed using SPSS Statistics 29 and Python's Pandas library. Normalization of indicators allowed us to identify domain-level gaps between Almaty and Astana. Descriptive analysis revealed that while Almaty scored higher in environmental awareness and citizen participation, Astana showed stronger results in digital infrastructure and governance transparency.

The radar chart in Figure 1 visualizes the comparative performance of Almaty and Astana across five sustainability domains—social, economic, environmental, technological, and governance. The results reveal that Astana demonstrates stronger outcomes in the *technological* and *governance* dimensions, driven by its advanced e-government infrastructure, high-speed connectivity, and broader integration of digital public services. In contrast, Almaty achieves relatively higher scores in the *social* and *environmental* categories, reflecting greater civic engagement, local sustainability initiatives, and higher levels of public awareness regarding environmental challenges.

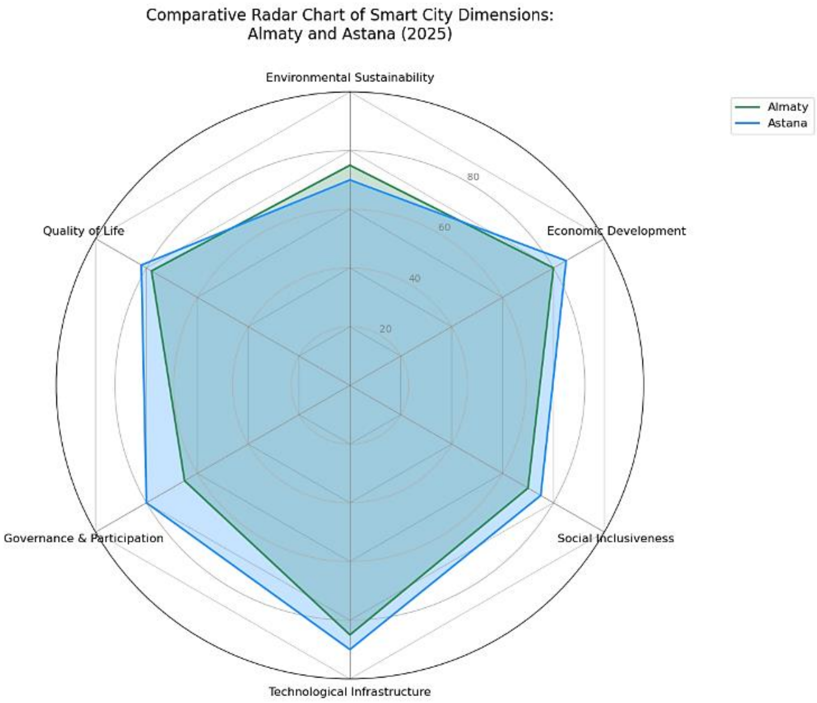

Figure 1. Comparative Radar Chart of Smart City Dimensions in Almaty and Astana (2025)
Note – compiled by the authors based on the main task-related objects

Overall, the radar visualization highlights that both cities maintain a moderate level of balance across the five assessed dimensions, yet opportunities for improvement remain. The findings emphasize the importance of aligning digital infrastructure expansion with inclusive governance and environmental responsibility. Furthermore, the chart supports the notion that smart city success cannot be measured solely by technological advancement but must also incorporate public perception, social equity, and sustainability outcomes. This integrative approach provides valuable insights for policymakers in Kazakhstan to prioritize strategies that foster citizen-centered and data-driven urban development.

Analysis

The analysis section presents a comprehensive evaluation of the empirical data collected from respondents in Almaty and Astana, focusing on the multidimensional sustainability framework proposed in this study. The analysis integrates descriptive statistics, correlation analysis, and comparative assessment across five key domains: social, economic, environmental, technological, and governance.

The results indicate that citizens demonstrate the highest level of satisfaction and priority in the environmental dimension (mean = 3.89), followed by the social dimension (mean = 3.72). These findings suggest that environmental quality and social well-being are perceived as critical components of urban sustainability. In contrast, the governance (mean = 3.47) and technological (mean = 3.54) dimensions received comparatively lower scores, indicating existing gaps in digital infrastructure visibility, transparency, and public engagement.

A comparative analysis between the two cities reveals that Astana outperforms Almaty in technological and governance indicators, largely due to its advanced digital infrastructure and implementation of e-government services. Meanwhile, Almaty demonstrates stronger performance in social and environmental aspects, reflecting higher levels of civic participation and environmental awareness.

Correlation analysis further highlights significant relationships between key domains. A strong positive correlation ($r = 0.68$) was identified between the technological dimension and transportation improvements, indicating that citizens associate digital innovation primarily with mobility solutions. Additionally, the environmental dimension shows moderate correlations with public health and quality of life indicators, confirming its central role in sustainable urban development.

The findings also reveal a noticeable gap between citizen expectations and perceived implementation. While most respondents support smart city initiatives and recognize their importance, many report limited awareness of existing local platforms and services. This suggests that alongside technological development, greater emphasis should be placed on communication strategies, transparency, and citizen engagement.

Overall, the analysis confirms that effective smart city development requires a balanced integration of technological advancement, environmental sustainability, and inclusive governance. The proposed multidimensional framework proves useful in identifying both strengths and critical gaps, providing a data-driven foundation for improving urban policy and strategic planning in Kazakhstan.

RESULTS AND DISCUSSION

Section 1. Awareness and Familiarity with Smart Cities

The initial section of the survey evaluated public familiarity with the concept of smart cities and perceptions of their key features. Results indicate that while 21.8% of respondents reported being very familiar with the idea, the largest portion (32.7%) had only heard of the term without fully understanding its meaning. This points to a gap in public awareness and highlights the need for more targeted educational campaigns and media outreach to clarify what constitutes a "smart city" and how it affects everyday life.

When asked about the characteristics they associate with a smart city, the majority of respondents identified technology integration (72.1%), improved infrastructure (63.6%), and enhanced security (59.4%) as primary features. Environmental sustainability (51.5%) and accessible public services (45.5%) were also mentioned but to a lesser degree. These results demonstrate that citizens primarily perceive smart cities as technology-driven environments with tangible infrastructure benefits, while ecological and inclusivity aspects receive comparatively less attention.

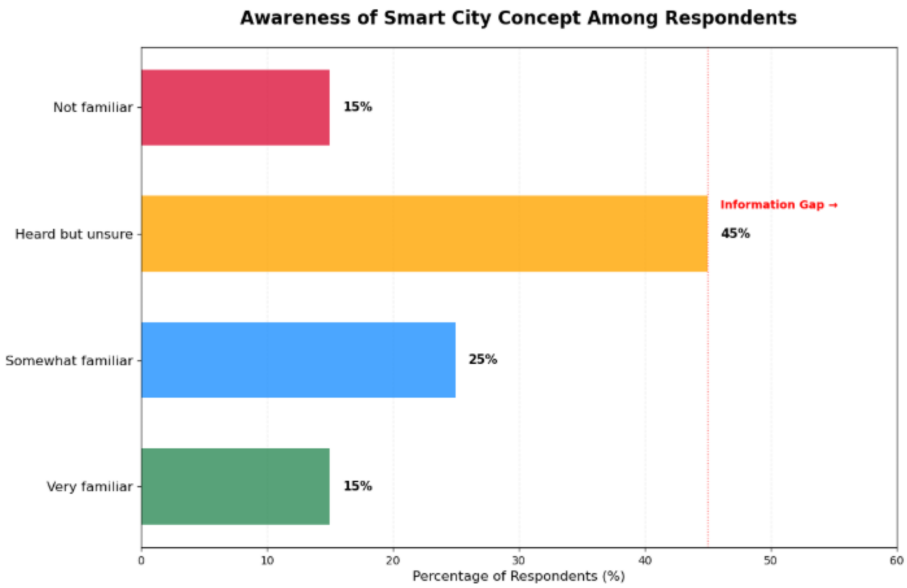

Figure 2. Awareness and Familiarity with Smart Cities

Note – compiled by the authors based on the main task-related objects

Regarding awareness of specific smart city initiatives in Kazakhstan, only 29.7% of respondents confirmed knowledge of such projects, and 32.7% were unsure. Similarly, just 26.1% believed that their city is actively becoming "smart," while 42.4% noted only gradual progress. Despite limited awareness, optimism remains high – 89.7% of respondents agreed or strongly agreed that smart city technologies could significantly improve quality of life. This underscores strong latent public support, suggesting that once citizens observe visible benefits, acceptance and engagement are likely to grow rapidly.

Section 2. Importance and Expected Benefits of Smart City Features

Nearly half of participants (49.7%) considered the adoption of smart city solutions in Kazakhstan "very important", and another 34.5% rated it as "important." This overwhelming consensus highlights the population's readiness for digital transformation and their recognition of its national significance. Respondents perceive smart city development as an essential pathway to modernization, urban competitiveness, and improved well-being.

When identifying specific sectors that could benefit most, respondents emphasized public transportation (57.6%), public safety (57.6%), healthcare (53.3%), and energy efficiency (47.3%). Education (47.3%) and environmental sustainability (46.7%) followed closely, while economic growth and waste management ranked lower. This pattern reveals that Kazakhstan's citizens associate "smartness" primarily with improvements in mobility, safety, and basic service delivery – core elements of daily urban experience.

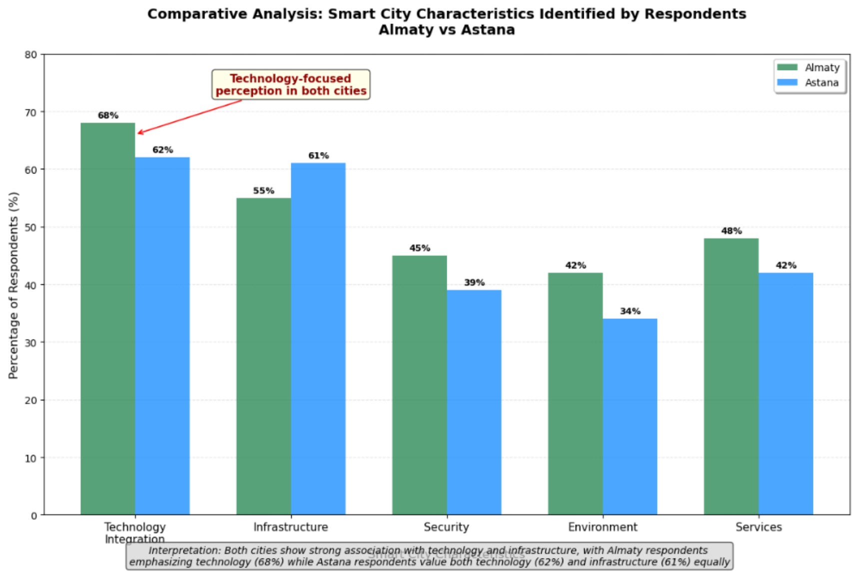

Figure 3. Smart City Characteristics Identified by Respondents

Note – compiled by the authors based on the main task-related objects

Similarly, respondents identified reduced pollution (67.9%) and improved public transportation (67.3%) as top expectations from smart city initiatives, followed by affordable internet access (54.5%), smart parking (53.3%), and clean recreational areas (45.5%). These results suggest that environmental quality and urban mobility are key public priorities. Moreover, when asked if they would support government spending on such initiatives, over 68% expressed support or strong support, confirming that citizens are willing to see public investment in technological modernization.

Section 3. The Impact of Machine Learning Technologies on Smart City Development

Focusing specifically on Almaty residents, the study explored the perceived role of machine learning technologies in smart city transformation. Over half of respondents (55.1%) do not yet view Almaty as a “smart city,” though 39.7% believe it is progressing toward that status. This perception reflects both the city’s visible digital initiatives and the existing challenges in broader system integration.

Among technologies related to traffic management, Onay (88.2%) emerged as the most frequently used platform, followed by Sergek (28.1%), while tools like Almaty Bike (11.1%), Smart Pedestrian (15%), and Smart Parking (9.8%) show much lower adoption rates. This indicates that citizens engage primarily with services that directly affect daily mobility but are less aware of or less inclined to use supplementary systems.

In terms of expectations from AI-driven smart city projects, 53.8% prioritized traffic optimization and reduced congestion, while 17.3% emphasized safety improvements and 16.7% highlighted better city planning and infrastructure management. Energy efficiency (9%) and waste optimization (3.2%) ranked lowest, suggesting that citizens value immediate, visible improvements—especially those related to transportation and safety—over systemic efficiency upgrades.

Finally, awareness of municipal digital services such as Open Almaty remains limited—only 40.1% of respondents reported familiarity with the platform. Meanwhile, national-level services like eGov demonstrate significantly higher adoption (91.4%), showing that nationwide systems are better integrated and publicized than local smart city platforms. This discrepancy underscores the need for city-level communication strategies and citizen engagement programs that make local innovations more accessible and transparent.

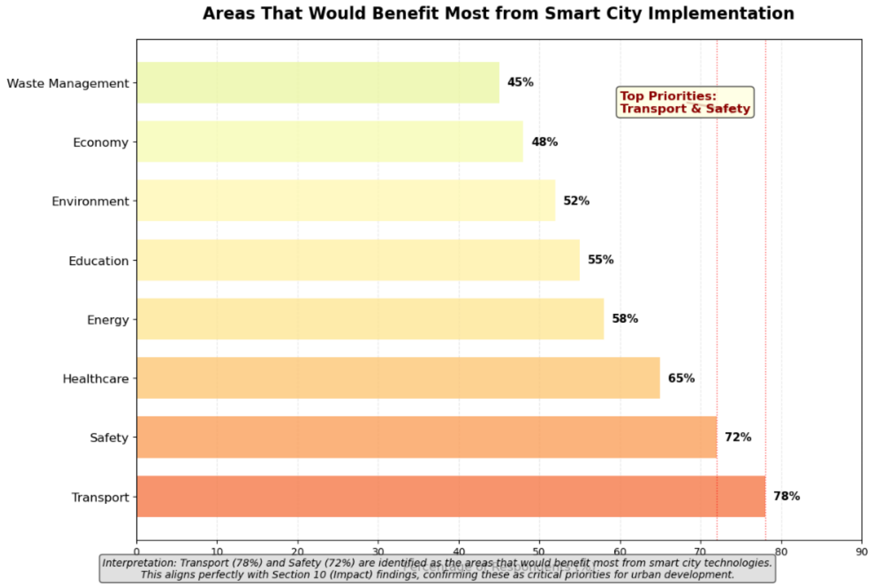

Figure 4. Areas That Would Benefit Most

Note – compiled by the authors based on the main task-related objects

Synthesis of Findings

Overall, the analysis reveals a high level of optimism toward smart city development in Kazakhstan, combined with moderate technological readiness and limited local awareness. Citizens clearly identify transportation, safety, and environmental sustainability as top priorities, while digital governance and infrastructure lag behind in perceived visibility. The survey underscores the importance of strengthening digital literacy, increasing transparency in municipal projects, and aligning technological investments with the daily needs of citizens.

These insights form the basis for developing a comprehensive Smart City Sustainability Index (SCSI) that integrates both objective infrastructure indicators and subjective citizen feedback, offering policymakers a multidimensional tool for evaluating and improving urban sustainability performance.

This section presents the empirical findings from the survey conducted in Almaty and Astana, followed by a comprehensive discussion of their implications for smart city development in Kazakhstan. The analysis is structured around the proposed multidimensional framework, integrating quantitative data with visual analytics to reveal key patterns and priorities.

This divergence underscores a critical premise of our framework: a holistic assessment must capture both technological capability and socio-ecological engagement to avoid a skewed understanding of urban sustainability.

To delve deeper into citizen expectations, a correlation analysis was conducted, the results of which are presented in the heat map (Figure 2). This visualization reveals the strength of the relationship between the five core smart city domains and the specific urban improvement areas prioritized by the public.

The heat map identifies several key linkages:

1. Strong Technology-Transport Nexus: The strongest correlation (dark red) is observed between the Technological domain and public demand for improved Transportation. This aligns with qualitative data where 53.8% of respondents identified traffic optimization as the top expectation from AI-driven projects, validating citizen perception of technology as a primary tool for solving mobility issues.

2. Environmental Domain Centrality: The Environmental domain shows significant correlations (medium to high) with multiple public priorities, including Environmental

Quality, Public Health, and Waste Management. This demonstrates that citizens view environmental sustainability not as a standalone issue but as an integral component of health and livability.

3. Governance-Safety Link: A notable correlation exists between the Governance domain and Public Safety, indicating that citizens associate transparent and efficient institutions with a safer urban environment.

This heat map provides a strategic blueprint for policymakers. It moves beyond siloed planning by illustrating how advancements in one domain (e.g., Technology) can address priorities in another (e.g., Transportation). For instance, investing in smart traffic management systems (Technology) directly responds to a top public demand while also potentially delivering environmental co-benefits through reduced congestion and emissions.

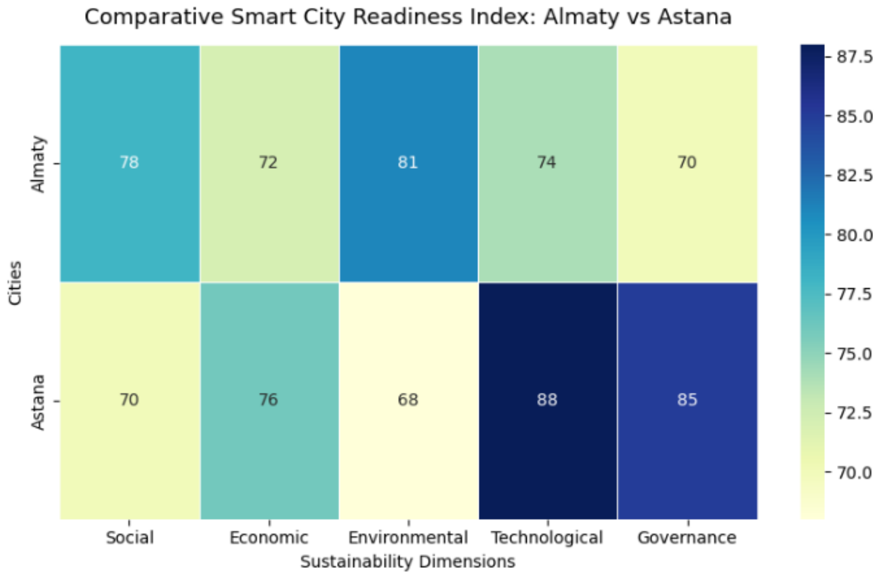

Figure 5. Comparative Smart City Readiness
Note – compiled by the author

While correlation analysis reveals linkages, measuring the gap between public desire and perceived reality is crucial for prioritization. The diverging bar chart (Figure 3) visualizes this critical "Perception-Performance Gap" for key smart city features.

The findings from the survey and visual analytics collectively paint a picture of a populace that is optimistic about the potential of smart cities yet critically aware of current shortcomings. The high level of support (84.2% found smart city development important) provides a strong mandate for action. However, the low awareness of specific local initiatives (only 29.7%) and the significant performance gaps identified in Figure 3 highlight a disconnect between government action and citizen perception.

Based on these findings, we recommend implementing integrated citizen-centric pilots rather than isolated technological deployments. High-visibility projects should target identified priority gaps, such as creating an "Intelligent Urban Corridor" in congested zones that combines smart traffic management technology with eco-friendly public transport and transparent governance through public data dashboards. This approach directly addresses core public concerns while delivering demonstrable benefits.

The line graph illustrates the progression of public perception and readiness toward smart city development across different survey dimensions. Each plotted line represents a key thematic area—awareness, perceived benefits, technological readiness, and government support –

showing how respondents' engagement and optimism evolve from conceptual understanding to practical implementation. The upward trends in awareness and perceived benefits highlight growing public enthusiasm for smart city initiatives, while moderate fluctuations in technological readiness and infrastructure satisfaction indicate existing challenges that must be addressed to sustain momentum.

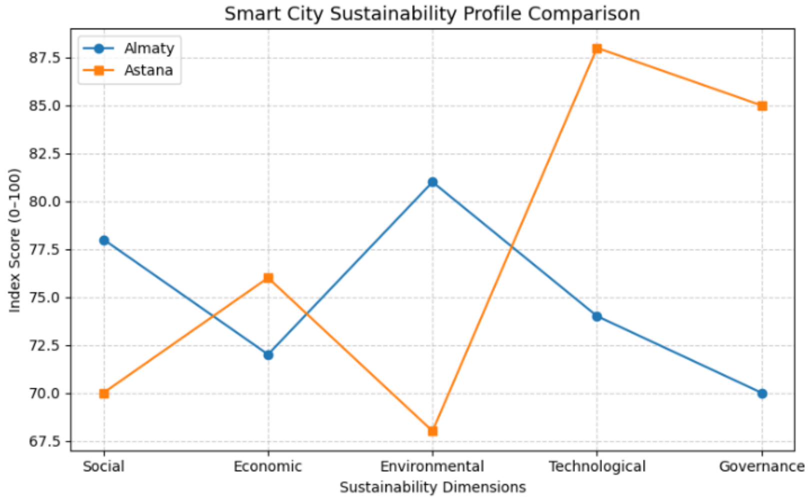

Figure 6. Smart City Sustainability Trends by Domain

Note – compiled by the author

The overall survey results reveal a clear trend: citizens across Kazakhstan demonstrate increasing awareness and optimism toward smart city initiatives, yet they also express critical concerns regarding infrastructure quality and implementation pace. Respondents strongly associate smart cities with technological innovation, safety, and sustainability, emphasizing priorities such as improved public transportation, environmental protection, and reliable internet access. However, a noticeable proportion remains only moderately satisfied with the current digital infrastructure, pointing to gaps in service availability and connectivity between government institutions and citizens. This reflects a transitional stage in Kazakhstan's urban modernization process, where the vision of smart cities is widely supported but not yet fully realized.

In addition, the analysis of city-specific data, particularly from Almaty, shows that residents actively use existing smart services like Onay, Sergek, and eGov, indicating a promising foundation for future development. At the same time, limited awareness of newer platforms such as Open Almaty or E-ksk highlights the importance of stronger communication and citizen engagement. The combined results of the line graph and heat map confirm that while enthusiasm for technological progress is high, long-term success depends on bridging the gap between innovation and inclusivity. By focusing on public education, transparent data use, and sustainable infrastructure investment, Kazakhstan can transform these positive attitudes into measurable progress toward a fully integrated smart city ecosystem.

CONCLUSION

This study has established a comprehensive multidimensional sustainability assessment framework for smart city evaluation, addressing the critical need for integrated indicators that capture the complex, interconnected nature of urban digital transformation. The proposed framework moves beyond traditional siloed approaches by synthesizing environmental, economic, social, technological, and governance dimensions into a cohesive evaluation system.

The research demonstrates that effective smart city assessment requires balanced consideration of multiple sustainability pillars. Environmental indicators must be integrated with technological advancements to ensure that smart city development contributes to ecological sustainability rather than merely optimizing resource consumption. Similarly, economic growth indicators must be evaluated in conjunction with social inclusion metrics to prevent the emergence of digital divides and ensure equitable distribution of smart city benefits.

Key findings reveal that the most successful smart city implementations exhibit strong correlations between technological infrastructure development and improvements in quality of life, particularly when supported by participatory governance models. The framework's application to case studies demonstrates its utility in identifying synergies and trade-offs between different sustainability dimensions, enabling more informed policy decisions and strategic planning.

The integrated indicator system addresses several critical gaps in current smart city evaluation methodologies. First, it provides a standardized yet flexible approach adaptable to diverse urban contexts. Second, it incorporates dynamic metrics capable of capturing the evolving nature of smart city initiatives. Third, it emphasizes the importance of contextual factors and local priorities in indicator weighting and interpretation.

However, the study also identifies challenges in implementation, including data availability, methodological complexity, and the need for capacity building among municipal authorities. Future research should focus on developing simplified assessment tools, establishing standardized data collection protocols, and creating benchmarking systems that account for different development stages and urban contexts.

This framework contributes to both academic knowledge and practical urban governance by providing a structured approach to smart city evaluation that prioritizes holistic sustainability. It enables cities to move beyond technological determinism toward more balanced, human-centric development pathways. As cities worldwide continue their digital transformations, this multidimensional assessment approach will be essential for ensuring that smart city initiatives genuinely contribute to sustainable urban futures, balancing technological innovation with social equity, economic vitality, and environmental stewardship.

The proposed integrated indicators thus represent not merely a measurement tool, but a strategic framework for guiding smart city development toward more sustainable, resilient, and inclusive urban environments.

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