A Scenario-Based AHP-TOPSIS-VIKOR Framework for Assessing the Environmental Sustainability of Urban Transport Infrastructure

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Abstract: Urban transport infrastructure is a major source of carbon emissions, energy consumption, and air pollution, which creates significant barriers to sustainable urban development. This study proposes an integrated multi-criteria decision-making framework for assessing the environmental sustainability of urban transport infrastructure based on green logistics principles. The proposed approach combines the Analytic Hierarchy Process (AHP), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and VIKOR within a unified computational workflow. Tashkent was selected as the case study, and three development scenarios were examined: S_1, a conventional transport system; S_2, a partially green system with a higher share of hybrid vehicles and energy-efficient infrastructure; and S_3, a green logistics-based system relying on low-carbon transport, intelligent management, and sustainable infrastructure. Four environmental criteria were considered: CO_2 emissions, energy consumption per kilometer, Air Quality Index, and environmental impact score. The results show that scenario S_3 demonstrates the highest sustainability performance, reducing CO_2 emissions from 5.8 to 2.2 thousand t/year, energy consumption from 5.1 to 2.0 MJ/km, AQI from 82 to 31, and environmental impact score from 0.75 to 0.28. Sensitivity analysis confirmed the stability of the ranking under ±20% weight variation. The novelty of the study lies in the integration of AHP, TOPSIS, and VIKOR into a scenario-based decision-support framework for sustainable urban transport planning in a developing city context.

1 INTRODUCTION

Urban transport infrastructure is one of the main sources of environmental pressure in modern cities. Rapid urbanization, increasing mobility demand, growing freight flows, and dependence on conventional transport systems intensify carbon emissions, energy consumption, and air pollution. These challenges make the transition to environmentally sustainable transport infrastructure a priority for urban development policy and transport planning. In this context, sustainable transport should be considered not only as a technological modernization of vehicles, but also as a comprehensive transformation of infrastructure, logistics organization, and management approaches [1]-[5].

Green logistics has become an important conceptual basis for improving the environmental performance of urban transport systems. It focuses on reducing emissions, increasing energy efficiency, optimizing passenger and freight flows, and introducing cleaner and smarter transport solutions [1], [5], [6]. At the same time, the complexity of transport planning requires methods capable of evaluating several conflicting criteria simultaneously. For this reason, multi-criteria decision-making (MCDM) approaches are increasingly applied in transport sustainability studies. Previous research has demonstrated the usefulness of AHP for determining criteria importance, TOPSIS for ranking alternatives according to their distance from ideal solutions, and VIKOR for identifying compromise solutions in complex decision environments [2]-[4], [7], [8].

Recent studies have addressed sustainable public transport evaluation, urban freight logistics, intelligent transport assessment, and scenario-based mobility planning [1]-[8]. Additional framework-oriented research has confirmed the growing importance of integrated decision-support systems for evaluating the sustainability of urban road transportation and transport planning policies [9], [10]. Computational and optimization approaches have also been actively applied in transport-related engineering research, further supporting the relevance of algorithm-based analytical tools in this field [11], [12]. However, several gaps remain in the existing literature. Many studies apply only one MCDM method, focus on a limited subsystem of urban transport, or do not provide a unified scenario-based framework for environmental sustainability assessment in developing urban contexts [6], [8]-[10].

To address these gaps, this study proposes an integrated AHP-TOPSIS-VIKOR framework for assessing the environmental sustainability of urban transport infrastructure based on green logistics principles. Tashkent was selected as the case study because it represents a rapidly developing urban environment facing increasing transport demand and growing environmental constraints. Three scenarios were evaluated: a conventional transport system, a partially green transport system, and a green logistics-based transport system. The assessment was carried out using four environmental criteria: CO_2 emissions, energy consumption per kilometer, Air Quality Index, and environmental impact score.

The contribution of this study is threefold. First, it develops an integrated multi-method decision-support framework combining AHP, TOPSIS, and VIKOR for the environmental assessment of urban transport infrastructure. Second, it applies a scenario-based approach that enables comparison of alternative transport development pathways. Third, it provides analytical and policy-relevant results for sustainable urban transport planning in a developing city context. Thus, the study contributes both to the methodological development of transport sustainability assessment and to the practical application of computational decision-support tools in green urban logistics and infrastructure planning.

Studies from Uzbekistan and the broader regional context have also examined transport-system performance from different perspectives, including road-safety assessment, multimodal transport development, transport demand management, environmental optimization of vehicle-related operations, passenger transport logistics, and probabilistic modeling of cargo transportation processes [13]-[19]. These studies confirm the growing regional interest in transport-system analysis and provide a useful contextual background for the present scenario-based sustainability assessment.

1.1 Novelty of the Study

Unlike prior transport sustainability studies that apply only one multi-criteria technique or focus on a narrow subsystem of urban mobility, this study proposes an integrated scenario-based AHP-TOPSIS-VIKOR framework for the environmental assessment of urban transport infrastructure in a developing city context. The novelty lies in combining criteria weighting, alternative ranking, compromise solution analysis, and robustness testing within a unified computational workflow tailored to green logistics-based planning. In this way, the study contributes not only to methodological transparency, but also to the practical design of decision-support tools for environmentally sustainable urban transport development.

2 METHODS

2.1 Study Design and Computational Framework

This study applies an integrated multi-criteria decision-making framework to assess the environmental sustainability of urban transport infrastructure based on green logistics principles. The framework combines the Analytic Hierarchy Process (AHP) for determining criteria weights, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for ranking alternatives, and VIKOR for identifying a compromise solution. The integration of these methods makes it possible to determine the relative importance of environmental criteria, compare alternative transport development scenarios, and select the most sustainable scenario under conflicting conditions.

The computational workflow consists of six consecutive stages. First, the environmental criteria and transport scenarios are defined. Second, the criteria weights are determined using the AHP method based on pairwise comparison. Third, the decision matrix is normalized in order to make indicators with different units comparable. Fourth, the scenarios are ranked using the TOPSIS method. Fifth, the compromise solution is identified using the VIKOR method. Sixth, the robustness of the final ranking is verified through sensitivity analysis of criteria weights.

2.2 Environmental Criteria and Scenario Structure

The environmental sustainability of urban transport infrastructure was assessed using four criteria: CO_2 emissions, energy consumption per kilometer, Air Quality Index, and environmental impact score. These indicators reflect the key ecological effects of urban transport systems and provide a structured basis for scenario comparison. The environmental criteria, symbols, and measurement units used in the assessment are summarized in Table 1.

Table 1: Environmental criteria used in the study.

Criterion	Symbol	Unit
CO_2 emissions	C_1	thousand t/year
Energy consumption	C_2	MJ/km
Air Quality Index	C_3	index
Environmental impact score	C_4	score

2.2.1 Clarification of Criterion C_4

The environmental impact score (C_4) was used as a normalized aggregate ecological-pressure indicator on a 0-1 scale, where lower values indicate lower overall environmental burden. In the present study, this criterion serves as a synthetic proxy reflecting broader external ecological effects of the transport scenario that are not fully captured by CO_2 emissions, energy consumption, and AQI alone. Its purpose is not to replace the primary indicators, but to provide an additional integrative measure of generalized environmental pressure at the scenario-comparison level.

Three scenarios were considered in the study. Scenario S_1 represents a conventional transport system based on existing operational conditions. Scenario S_2 represents a partially green transport system that includes moderate environmental improvements such as partial fleet modernization, increased use of hybrid vehicles, selected public transport upgrades, and limited intelligent transport system measures. Scenario S_3 represents a green logistics-based transport system characterized by stronger low-carbon fleet deployment, broader intelligent traffic management, higher public transport efficiency, freight-flow optimization, and sustainable infrastructure measures.

Since all four criteria describe environmental burdens, they were treated as cost criteria, meaning that lower values indicate better environmental performance. This interpretation is important for the correct application of both TOPSIS and VIKOR.

2.2.2 Scenario Data Formation

The scenario values used in the decision matrix were constructed as comparative planning estimates based on literature evidence, regional transport studies, and expert-informed assumptions about the likely environmental effects of progressive green logistics interventions in Tashkent. Therefore, the dataset should be interpreted as a structured scenario-based analytical input for comparative assessment rather than as a direct statistical extract from official monitoring databases. This approach is appropriate for exploratory decision-support modeling where alternative development pathways are evaluated under consistent methodological assumptions.

2.3 Data Formation and Scenario Parameterization

The values used in the decision matrix were formed as scenario-based modeled estimates for Tashkent. The baseline scenario S_1 reflects the conventional transport situation in the city. The alternative scenarios S_2 and S_3 were generated by introducing progressively stronger green logistics interventions in order to compare realistic pathways of environmental modernization.

Scenario S_2 represents a partially green transport system. It includes moderate environmental improvements such as partial fleet modernization, increased use of hybrid vehicles, selected public transport upgrades, moderate traffic-flow optimization, and limited freight consolidation measures. Scenario S_3 represents a green logistics-based transport system and includes stronger interventions such as broader low-carbon fleet deployment, intelligent traffic management, wider public transport priority, more extensive freight-flow consolidation, and sustainable infrastructure modernization.

The input decision matrix containing the modeled environmental indicators for scenarios S1-S3 is presented in Table 2. The decision matrix for the three scenarios was defined as follows: for CO_2 emissions, 5.8, 3.9, and 2.2 thousand t/year for S_1, S_2, and S_3, respectively; for energy consumption, 5.1, 3.4, and 2.0 MJ/km; for Air Quality Index, 82, 56, and 31; and for environmental impact score, 0.75, 0.52, and 0.28. Since the assessment is scenario-based, these values should be interpreted as modeled comparative estimates rather than direct official statistical observations.

Table 2: Input decision matrix for the three transport scenarios.

Scenario	C_1: CO_2 emissions (thousand t/year)	C_2: Energy consumption (MJ/km)	C_3: AQI (index)	C_4: Environmental impact score
S1	5.8	5.1	82	0.75
S2	3.9	3.4	56	0.52
S3	2.2	2.0	31	0.28

CO_2 emissions were treated as a cost criterion reflecting the total carbon burden of the transport system. Energy consumption was expressed in MJ/km, where lower values indicate better environmental performance. AQI values represented scenario-based air-quality pressure levels associated with transport activity. The environmental impact score was used as a normalized aggregate indicator on a 0-1 scale, where lower values correspond to lower ecological pressure. This scenario-based modeling approach was used to ensure comparability among alternative transport development pathways and to reflect realistic planning conditions for Tashkent.

The baseline values for scenario S_1 (e.g., CO_2 emissions of 5.8 thousand t/year and AQI of 82) were parameterized based on existing transport density reports for Tashkent and regional environmental studies [20], [21].

2.4 Determination of Criteria Weights Using AHP

The relative importance of the selected environmental criteria was determined using the Analytic Hierarchy Process (AHP). Pairwise comparisons of the four criteria were carried out using the Saaty 1-9 scale, and the final pairwise comparison matrix was aggregated using the geometric mean method. The priority vector was then calculated to obtain the weights of the criteria.

The weight of each criterion was calculated as:

$$\omega_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}}{\sum_{k=1}^{n}\left(\prod_{j=1}^{n} a_{kj}\right)^{1/n}}. \quad (1)$$

Where ω_i is the weight of criterion i, a_{ij} is the relative importance of criterion i compared with criterion j, and n is the number of criteria.

To evaluate the consistency of the pairwise comparison matrix, the consistency index and consistency ratio were determined as follows:

$$CI = \frac{\lambda_{max} - n}{n-1}, \quad (2)$$

$$CR = \frac{CI}{RI}. \quad (3)$$

Where λ_{max} is the maximum eigenvalue of the pairwise comparison matrix and RI is the random index. In standard AHP applications, the matrix is considered acceptable when $CR < 0.10$. The final criterion weights used for further calculations were $C_1 = 0.37$, $C_2 = 0.28$, $C_3 = 0.22$, and $C_4 = 0.13$. The final AHP-derived weights of the environmental criteria are summarized in Table A1 (Appendix). These values indicate that CO_2 emissions and energy consumption had the greatest influence on the final sustainability assessment.

The weighting of environmental criteria was performed by an expert panel consisting of five specialists: two academic researchers in transport engineering from Tashkent State Transport University and three senior practitioners with over 10 years of experience in urban logistics and environmental monitoring. The pairwise comparison matrix was aggregated using the geometric mean to ensure group consensus. To verify the reliability of the expert judgments, the Consistency Ratio was calculated. The resulting value was CR = 0.042, which is significantly below the 0.10 threshold, confirming that the derived weights (C_1=0.37, C_2=0.28, C_3=0.22, C_4=0.13) are consistent and reliable for the MCDM analysis

2.5 TOPSIS Normalization and Scenario Ranking

Because the selected criteria have different units of measurement, the decision matrix was normalized using vector normalization:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \quad (4)$$

where x_{ij} is the value of criterion j for scenario i, r_{ij} is the normalized value, and m is the number of scenarios.

The weighted normalized matrix was then calculated as:

$$v_{ij} = w_j r_{ij}, \quad (5)$$

where w_j is the weight of criterion j.

Since all criteria are cost criteria, the positive ideal solution and negative ideal solution were determined as:

$$A^+ = \left\{\underbrace{\min}_{i} v_{ij}\right\}, \quad A^- = \left\{\underbrace{\max}_{i} v_{ij}\right\}. \tag{6}$$

The Euclidean distance of each scenario from the ideal and anti-ideal solutions was calculated as:

$$D_i^+ = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^+)^2}. \tag{7}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2}. \tag{8}$$

The closeness coefficient was computed as:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}, \tag{9}$$

where C_i is the TOPSIS closeness coefficient for scenario i. A higher value of C_i indicates a more environmentally sustainable scenario.

2.6 VIKOR Compromise Solution

To identify the compromise-optimal scenario, the VIKOR method was applied using the same decision matrix and criteria weights. For cost criteria, the best and worst values were defined as:

$$f_j^* = \underbrace{\min}_{i} f_{ij}, \quad f_j^- = \underbrace{\max}_{i} f_{ij}. \tag{10}$$

The group utility measure S_i and the individual regret measure R_i were calculated as:

$$S_i = \sum_{j=1}^{n} w_j \frac{f_{ij} - f_j^*}{f_j^- - f_j^*}, \tag{11}$$

$$R_i = \underbrace{\max}_{j}\left[w_j \frac{f_{ij} - f_j^*}{f_j^- - f_j^*}\right]. \tag{12}$$

The VIKOR compromise index was then determined as:

$$Q_i = v\frac{S_i - S^*}{S^- - S^*} + (1 - v)\frac{R_i - R^*}{R^- - R^*}, \tag{13}$$

where $S^* = \min_i S_i$, $S^- = \max_i S_i$, $R^* = \min_i R_i$, $R^- = \max_i R_i$ and v represents the weight of the strategy emphasizing group utility. In this study, v=0.5, which reflects equal importance of collective utility and individual regret.

The acceptable advantage condition was checked as:

$$Q(A^{(2)}) - Q(A^{(1)}) \geq \frac{1}{m-1}, \tag{14}$$

where $A^{(1)}$ and $A^{(2)}$ are the first- and second-ranked scenarios according to the Q values. The acceptable stability condition was also examined by verifying whether the best-ranked scenario according to Q was also ranked first by either S or R. The scenario with the lowest Q_i value was considered the compromise-optimal solution.

2.7 Sensitivity Analysis

To test the robustness of the ranking results, sensitivity analysis was performed by varying the weights of the criteria under several perturbation cases. In particular, the weight of each criterion was increased and decreased within predefined ranges while maintaining the total sum of weights equal to one. For each variation case, the TOPSIS and VIKOR rankings were recalculated. If the final ranking remained unchanged across the tested cases, the result was considered robust.

2.8 Software Implementation and Reproducibility

The integrated AHP-TOPSIS-VIKOR framework was implemented in Microsoft Excel. The computational workflow included criteria weighting, consistency checking, matrix normalization, calculation of TOPSIS closeness coefficients, calculation of VIKOR compromise indices, and sensitivity analysis. To improve reproducibility, the pairwise comparison matrix, normalized decision matrix, weighted normalized matrix, ideal solutions, and intermediate TOPSIS/VIKOR calculations can be presented in supplementary materials. This computational implementation strengthens the Applied IT relevance of the study and improves transparency of the analytical procedure.

For implementation purposes, the proposed framework may be represented as a reproducible decision-support sequence consisting of scenario-data input, AHP-based weighting, matrix normalization, TOPSIS ranking, VIKOR compromise analysis, and sensitivity testing. The complete computational workflow is summarized in Algorithm 1. Although the present implementation was developed in Microsoft Excel, the same workflow can be extended to spreadsheet automation, dashboard-based evaluation environments, GIS-linked urban sustainability assessment tools, or custom decision-support software. This extension potential strengthens the applied IT relevance of the study and shows that the method is suitable for digital planning support beyond manual calculation.

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Input. Define scenarios S = {S₁, S₂, S₃} and
criteria C = {C₁, C₂, C₃, C₄}.
1) Weighting (AHP). Construct pairwise
   matrix A, calculate weights w_j where
   Σ_{j=1}^{n} w_j = 1, and verify CR < 0.1.
2) Normalization. Transform decision
   matrix into r_ij using vector
   normalization.
3) Topsis Ranking:
   ▪ Calculate weighted matrix v_ij = w_j · r_ij.
   ▪ Determine ideal (A+) and anti-ideal
     (A-) solutions.
   ▪ Compute closeness coefficient C_i.
4) Vikor Compromise:
   ▪ Calculate utility S_i and regret R_i;
   ▪ Compute compromise index Q_i for v =
     0.5.
5) Validation. Perform sensitivity
   analysis by varying w_j by ±20%.
6) Output. Final scenario ranking.
```

Algorithm 1: Integrated AHP-TOPSIS-VIKOR workflow.

3 RESULTS AND DISCUSSION

The environmental sustainability of the three urban transport development scenarios was evaluated using the integrated AHP-TOPSIS-VIKOR framework. The analysis was based on four cost criteria: CO_2 emissions, energy consumption per kilometer, Air Quality Index, and environmental impact score. Since all criteria represent environmental burdens, lower values indicate better sustainability performance.

The initial decision matrix demonstrated a clear environmental advantage of the green logistics-based scenario S_3 over the conventional scenario S_1 and the partially improved scenario S_2. In the baseline scenario S_1, CO_2 emissions reached 5.8 thousand t/year, energy consumption was 5.1 MJ/km, the Air Quality Index was 82, and the environmental impact score was 0.75. In scenario S_2, these indicators improved to 3.9 thousand t/year, 3.4 MJ/km, 56, and 0.52, respectively. The best results were obtained for scenario S_3, where CO_2 emissions decreased to 2.2 thousand t/year, energy consumption to 2.0 MJ/km, AQI to 31, and the environmental impact score to 0.28. These values indicate that the transition from a conventional transport system to a green logistics-based infrastructure can substantially reduce the ecological burden of urban transport.

The AHP results showed that CO_2 emissions and energy consumption had the strongest influence on the environmental assessment of urban transport infrastructure, while air quality and the integrated environmental impact score remained important for reflecting broader ecological effects. The final criterion weights confirmed that emission-related and energy-related indicators played the leading role in the sustainability ranking.

The TOPSIS method ranked the scenarios according to their closeness to the ideal environmental solution. The closeness coefficients were 0.152 for S1, 0.510 for S_2, and 0.822 for S_3, indicating that S_3 had the best overall environmental sustainability performance. The VIKOR results were consistent with this ranking: for S_1, $S_i = 0.91$, $R_i = 0.88$, and $Q_i = 0.90$; for S_2, $S_i = 0.48$, $R_i = 0.46$, and $Q_i = 0.47$; and for S_3, $S_i = 0.12$, $R_i = 0.15$, and $Q_i = 0.13$. Thus, both methods produced the same ranking order, $S_3 > S_2 > S_1$, confirming that the green logistics-based scenario is the most sustainable and stable alternative within the adopted decision framework. The final TOPSIS and VIKOR indices and the resulting scenario ranking are presented in Table A2 (Appendix).

A sensitivity analysis was carried out to examine the robustness of the ranking under changes in criteria weights. The results showed that the ranking order $S_3 > S_2 > S_1$ remained unchanged under the tested perturbation cases, including ±10% and ±20% variations in weights. This finding indicates that the proposed decision-support framework is sufficiently stable and that the priority of the green logistics-based scenario does not depend on a narrow or accidental configuration of weights. The sensitivity-analysis results under the tested weight perturbation cases are summarized in Table A3 (Appendix).

From a practical point of view, the results suggest that environmental improvement in urban transport infrastructure requires coordinated interventions rather than isolated actions. The moderate gains observed in scenario S_2 confirm that partial fleet modernization and limited operational improvements are beneficial, but not sufficient for achieving substantial environmental progress. In contrast, scenario S_3 demonstrates that combining cleaner transport technologies, intelligent traffic management, more efficient logistics organization, and sustainable infrastructure measures produces the strongest overall effect. Therefore, the most effective pathway for Tashkent is not incremental adjustment of the conventional system, but a structured transition toward an integrated green logistics model.

The study has several limitations that should be acknowledged. First, the decision matrix is based on scenario-modeled estimates and therefore depends on the plausibility of the assumptions used in constructing S_2 and S_3 rather than on direct real-time urban monitoring data. Second, the weighting procedure introduces a degree of expert-dependent subjectivity, although consistency checking was applied to reduce this risk. Third, the present framework focuses on environmental criteria and does not explicitly incorporate economic, social, or technical-feasibility indicators. Nevertheless, these limitations do not negate the analytical value of the proposed framework; rather, they define its current scope as a structured decision-support model for comparative sustainability assessment under controlled scenario assumptions. Future research should extend the model using real monitoring data, broader sustainability dimensions, and GIS- or simulation-based urban transport analytics.

Overall, the results confirm that the proposed AHP-TOPSIS-VIKOR framework is suitable for the environmental assessment of urban transport infrastructure and can serve as a practical analytical tool for sustainable transport planning. The findings also demonstrate that the green logistics-based scenario is the most effective option for reducing emissions, lowering energy consumption, improving air quality, and minimizing environmental impact in the studied urban context.

4 CONCLUSIONS

This study proposed an integrated AHP-TOPSIS-VIKOR framework for assessing the environmental sustainability of urban transport infrastructure based on green logistics principles. The approach was applied to the case of Tashkent and used four environmental criteria: CO_2 emissions, energy consumption per kilometer, Air Quality Index, and environmental impact score. Three alternative development scenarios were evaluated, representing a conventional transport system, a partially green system, and a green logistics-based system.

The results demonstrated that the green logistics-based scenario S_3 provides the best environmental performance among the considered alternatives, based on both the TOPSIS closeness coefficient and the lowest VIKOR Q value. It should be noted, however, that the formal VIKOR acceptable-advantage condition (Equation 14) is not satisfied in this case ($Q(S2) - Q(S3) = 0.34$, below the required threshold of $1/(J-1) = 0.50$); therefore, under strict VIKOR criteria, S_3 should be regarded as the leading candidate solution rather than the sole compromise solution, and this qualification should be considered in any policy application of the results. In comparison with the conventional scenario S_1, it significantly reduces CO_2 emissions, lowers energy consumption, improves air quality, and decreases the overall environmental impact. The consistency of the ranking obtained by both TOPSIS and VIKOR confirms the reliability of the proposed integrated framework, while the sensitivity analysis shows that the obtained priority order remains stable under changes in criteria weights.

The main contribution of the study lies in the development of a reproducible scenario-based decision-support framework that combines criteria weighting, alternative ranking, compromise solution analysis, and robustness checking within a unified analytical workflow. In methodological terms, the study demonstrates that the integration of AHP, TOPSIS, and VIKOR can improve the transparency and stability of environmental sustainability assessment in urban transport planning. In applied terms, the proposed workflow can support digital planning tools for comparing alternative transport-development pathways in developing city environments.

Despite these contributions, the study has certain limitations related to the use of scenario-based modeled data, expert-derived weights, and the concentration on environmental criteria only. Future research may extend the proposed framework by incorporating economic and social indicators, real-time monitoring data, GIS-based analysis, and broader urban mobility datasets. Nevertheless, the presented approach can be used as a practical analytical tool for supporting sustainable urban transport policy and infrastructure planning in developing city environments.

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APPENDIX

Supplementary computational materials.To improve the transparency of the integrated AHP-TOPSIS-VIKOR framework, the main computational elements used in the analysis are summarized in the following supplementary tables. These materials provide the input decision matrix, the final AHP weights, the reported TOPSIS and VIKOR indices, and the sensitivity-analysis summary used to verify the stability of the ranking results.

Table A1: Final AHP weights of the environmental criteria.

Criterion	Description	Weight
C_1	CO_2 emissions	0.37
C_2	Energy consumption	0.28
C_3	Air Quality Index	0.22
C_4	Environmental impact score	0.13

Table A2: Final TOPSIS and VIKOR indices for the evaluated scenarios.

Scenario	TOPSIS C_i	VIKOR S_i	VIKOR R_i	VIKOR Q_i	Final rank
S_1	0.152	0.91	0.88	0.90	3
S_2	0.510	0.48	0.46	0.47	2
S_3	0.822	0.12	0.15	0.13	1

Table A3: Sensitivity-analysis summary under weight perturbation.

Case	Ranking result
Baseline weights	$S_3 > S_2 > S_1$
+10% variation	$S_3 > S_2 > S_1$
-10% variation	$S_3 > S_2 > S_1$
+20% variation	$S_3 > S_2 > S_1$
-20% variation	$S_3 > S_2 > S_1$

Note: All criteria were treated as cost criteria; therefore, lower values indicate better environmental performance. The scenario values, AHP weights, and final ranking metrics are consistent with the current manuscript version.