

Article

A Combined AHP–TOPSIS-Based Decision Support System for Highway Pavement Type Selection

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Abstract

In Turkey, flexible pavement containing bituminous material is widely preferred on highways. Rigid pavement, which is based on concrete, is generally used in small-scale, specific projects. This situation, which has arisen due to historical and technical reasons, has also brought with it certain prejudices against rigid pavement applications. A review of the literature reveals that many factors influence the choice of highway pavement type, but decision-makers tend to make their selection based on the most important factors, disregarding other parameters. The lack of a systematic factor analysis is a shortcoming in this regard. In this research, a combined multi-criteria decision-making study was conducted, including the neglected factors, to address this technical deficiency in the pavement type selection process. Through detailed analysis, parameters likely to influence pavement type selection were identified and analyzed using the hybrid AHP–TOPSIS approach, guided by the opinions of experts in the field. The analysis shows that comfort (user ride quality), financial, and environmental factors are the most effective main criteria, while maintenance and repair costs, eco-friendliness, and initial construction costs were identified as the most critical sub-criteria influencing the choice of pavement type. Based on the analysis results, a detailed decision support system was presented to decision-makers according to the characteristics of the alternatives obtained. The results highlight the need for decision-making frameworks that prioritize both long-term cost efficiency and user safety, contributing to more sustainable and resilient pavement applications.



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Keywords: highway pavement; multi-criteria decision making; analytic hierarchy process; technique for order preference by similarity to ideal solution

1. Introduction

Highway pavements are examined under two general headings: rigid and flexible pavements. It has been observed that the type of highway pavement commonly used in Turkey consists of bitumen-based pavement materials, defined as flexible pavement. Understanding the fundamental reason for this is only possible with knowledge of political history. Asphalt road construction first began in Turkey in 1929, and until the late 1950s, highways were seen only as a complementary element to railways. After the 1950s, with the impact of the Marshall Plan, a petroleum-based paving type was adopted, and highway-focused planning continued until the 2000s [1]. In Turkey, flexible pavement is still predominantly used due to reasons such as the availability of pavement construction equipment, the ease of finding experienced personnel, and the abundance of experience. However, rigid pavement also has some important advantages over flexible pavement,

despite its negative characteristics. Properties such as not transferring deformations between different layers, providing high bending strength, low repair costs, being able to be laid directly on the subgrade, being less affected by subgrade strength, and not being damaged by oils are the advantages of rigid pavement over flexible pavement [2]. A typical structural of flexible and rigid pavements is illustrated in Figure 1 [3].

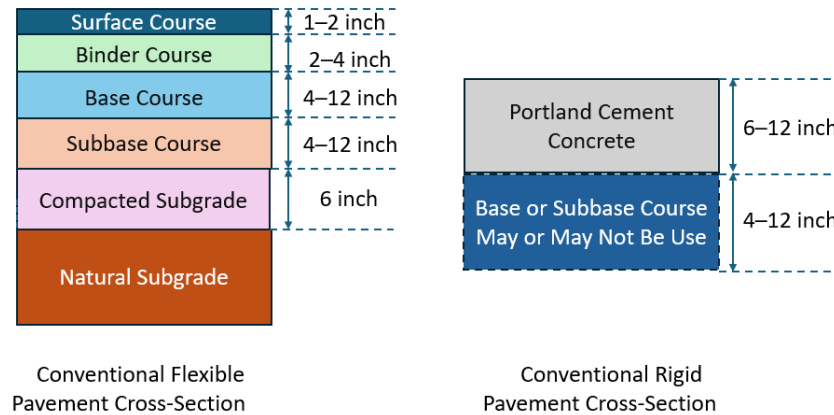


Figure 1. Illustration of the typical structural composition of flexible and rigid pavements, adapted from Huang (2004) [3].

Among the key performance characteristics, the likelihood of crack formation differs significantly between the two pavement types, and there are pretty different image-based [4], deep learning-supported [5], preventive maintenance-focused methods [6] available to detect this. Rigid pavements and flexible pavements typically experience different fatigue mechanisms. Understanding these different failure mechanisms is crucial for selecting the most suitable pavement type for local conditions. Understanding these behaviors also guides the development of design and performance evaluation methods. In this context, design guidelines such as the Mechanical–Empirical Pavement Design Guide (MEPDG) [7] have linked pavement material properties, traffic load, and climate conditions to expected deterioration levels and have played an important role in performing pavement performance evaluation, especially in the United States. While it is known that empirical-based pavement design methods developed in the early 1970s are still used in Europe, it is possible to say that the transition to mechanistic–empirical methods has been completed in the USA [8]. The South African Mechanistic Pavement Design Method (SAMDM) has been used in both new and rehabilitation pavement designs since the 1970s and has been validated through accelerated testing using heavy vehicle simulators [9]. However, such guided approaches require big data and calibration, which may limit the applicability of the method in developing countries such as Turkey, where the decision-making process often relies on expert judgment.

In order to eliminate this bias towards rigid pavement in the selection of pavement type, it is considered necessary to apply new evaluation methods. Accordingly, this study aims to establish a systematic and objective framework that evaluates pavement types through a set of clearly defined technical, economic, and sustainability-related criteria.

Furthermore, one of the most common problems faced by decision-makers in the transportation sector is the complexity of the process of deciding on the pavement type [10]. For this reason, determining the correct pavement type may require more time than expected or, in situations where a decision must be made quickly, may lead to the selection of the wrong pavement type. The main reason for this is that only the parameters that are obviously important are considered for pavement selection, while other parameters are ignored. Determining the importance levels of these factors and developing a decision

support methodology to decide on the pavement type based on this will save both time and performance. Therefore, the main objective of this study is to develop a decision support system for pavement type selection based on diverse factors. Given the multi-dimensional nature of pavement type selection, AHP and TOPSIS provide a structured way to integrate both subjective and objective criteria.

In order to achieve the study objective, analytical hierarchy process (AHP) and technique for order preference by similarity to ideal solution (TOPSIS) methods were used for calculating the weights of the factors and ranking of the alternatives, respectively. In this study, the AHP and TOPSIS methods were applied together for the first time to ensure that different qualitative and quantitative criteria were evaluated within a comprehensive, systematic, and transparent decision-making framework. This study is expected to contribute to theory and practice by proposing a novel and hybrid decision support system that can be used for selecting the most proper pavement type.

2. Literature Review

Road transportation is the most flexible mode of transport in terms of route, time, and travel speed. Considering the intense urbanization processes of the 21st century, the need for improving roads and transportation infrastructure has emerged. The demand for better road services has always been accompanied by criteria such as cost-effectiveness and durability. From the perspective of durability and cost-effectiveness, flexible and rigid pavements are always in competition with each other [2]. Flexible and rigid pavements have different characteristics, and the choice of which pavement to use depends on the expected advantages. Rigid pavements do not transfer deformations between layers, unlike flexible pavements. The load transfer in rigid pavements is based on flexural movement, while in flexible pavements, it is based on particle-to-particle contact.

Rigid pavements require a reasonably good subgrade, have high initial costs, and low repair costs. In contrast, flexible pavements depend heavily on subgrade quality and involve lower initial yet higher repair costs over time. Thermal stresses are critical for rigid pavements, but not for flexible ones. Rigid pavements cannot be opened to service immediately after construction, whereas flexible pavements can be opened much faster. Rigid pavements require thinner layers, while flexible pavements require thicker ones. Rigid pavements provide better night visibility and cause more noise than flexible pavements. Infrastructure work is more challenging on rigid pavements than on flexible pavements, and the fuel consumption of vehicles on rigid pavements is lower compared to flexible pavements. Rigid pavements require expansion joints, while flexible pavements do not. The cement concrete, reinforced or prestressed concrete materials used in rigid pavements are not damaged by oil and chemicals, whereas the hot asphalt concrete and granular materials used in flexible pavements are significantly affected by oils and chemicals [11].

Due to these differences between flexible and rigid pavements, many studies have been conducted on pavement types. One study conducted in the Mojokerto Region of Indonesia [12] compared the construction time and cost of both pavement types and concluded that rigid pavements are more economical. A more innovative study [13] examined different application processes for composite structures based on the combination of rigid and flexible pavements and discussed how to combine the advantages of both systems. Another study [14] analyzed the life-cycle costs of flexible and rigid pavements using criteria such as initial construction costs, maintenance, and repair expenses. It found that flexible pavements are a more cost-effective option than rigid pavements under various traffic conditions and pavement thicknesses, although it noted that the actual performance in the field would determine their effectiveness. As seen from all these studies, flexible and rigid pavements have always been a significant choice in road construction. Although there

are many factors influencing the selection of pavement type, decision-makers often focus on identifying the most important parameters while neglecting other parameters. A 2019 study [15] noted that the most important parameter in the design of flexible pavements is the modulus of elasticity of the subgrade, while for rigid pavements, it is the modulus of elasticity of the concrete. A 2015 study [16] applied an optimization model aimed at reducing total maintenance costs and increasing road quality by using inputs such as damage, deterioration parameters, traffic load, and climate conditions for the continuous maintenance and rehabilitation decisions of flexible pavements. However, this data was not evaluated for pavement selection. Another study conducted in 2021 [17] examined how the parameters used in road management systems affect the quality of these systems and found that the quality of them is significantly influenced by the correct selection of parameters. According to a 2011 report [18], economic and non-economic criteria are considered when selecting pavement type. Economic criteria include initial construction and rehabilitation costs, maintenance and repair costs, operating costs, salvage value, and life cycle cost analysis, while non-economic criteria include traffic volume, functional class of the road, climate, drainage, soil properties, noise levels, road safety, road comfort, construction time, job safety, recyclability, carbon footprint, and material conservation. A 1998 study [19] prioritized initial construction costs, rehabilitation costs, preventive and routine maintenance costs, vehicle operating expenses, other costs, and performance criteria as primary factors, while ease of construction, recyclability, maintainability, material availability, local preferences, and political decisions were considered secondary factors. A 2013 study [20] found that material accessibility, operational environment, the purpose of the road, and the natural environment are important factors in pavement type selection, while another study [21] claimed that socially effective criteria were often ignored alongside construction costs. A 2006 study [22] suggested that while functionality and safety criteria were considered in the traditional approach to transportation infrastructure design, environmental impacts, cultural sensitivities, and esthetic values were not prioritized as design criteria. A development, social benefit, and access-focused study [23] argued that, in addition to technical and financial criteria, access and social benefits should also be considered in pavement type selection. In a purely technical study [24], cost optimization and engineering parameters were emphasized. The common thread of all these different approaches is that creating a systematic mechanism for making the correct pavement type selection is of great importance for decision-makers.

In the literature, various studies have provided information on the parameters that directly influence pavement type selection and those that are often ignored. While the need for systematic parameter analysis and the determination of impact rates to guide decision-makers has been frequently mentioned, no study has yet been found in this regard. However, the applicability of these methodological conclusions to developing countries such as Turkey remains limited; therefore, existing frameworks need to be adapted in line with local technical capacity, data access, and institutional context. The main gap that this study aims to address is the systematic parameter analysis. In recent years, MCDM techniques have been increasingly applied to infrastructure decision-making problems in order to make the decision-making process more transparent [25,26]. Additionally, conducting these analyses using multi-criteria decision-making methods will also provide an innovative contribution to the literature.

3. Study Area

The study area is Istanbul Province, a city characterized by extremely high levels of repetitive loads, where according to 2024 data [27], 41% of drivers experience traffic congestion, and which has a Mediterranean climate according to the Köppen climate

classification [28,29], specifically Csa, meaning mild winters and very hot, dry summers. According to 2024 data [30], Istanbul is a metropolitan area with a population of 15.7 million. Istanbul, with its bridges, tunnels, and extensive highway network, connects Europe and Asia and is Turkey's most important economic and logistics hub. The rugged topography surrounding the city, varying ground conditions, and heavy truck traffic place significant stress on road surfaces. With these characteristics, Istanbul offers an extremely suitable and highly representative study area for evaluating pavement performance under heavy traffic and challenging climatic conditions. A location map of the study area is provided in Figure 2.

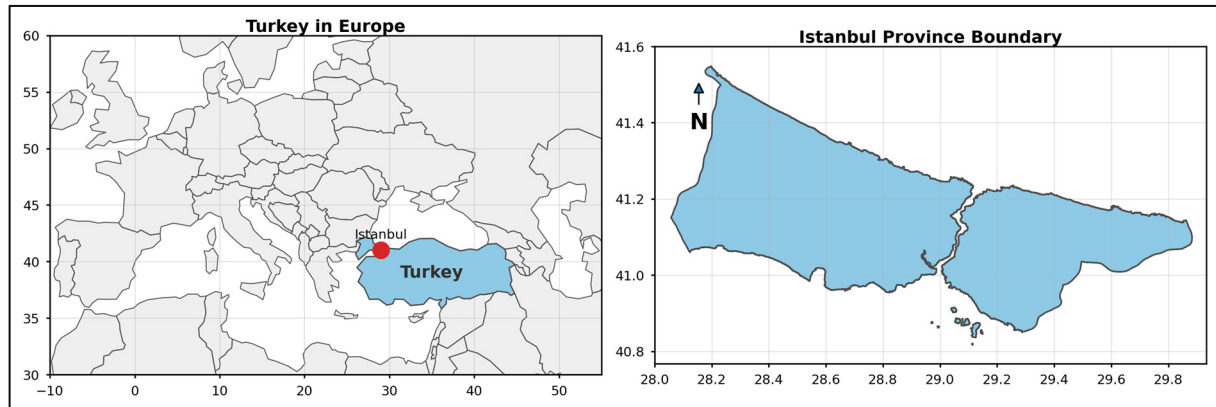


Figure 2. Study Area.

4. Methodology

4.1. Conceptual Framework

Within the scope of this study, a problem definition was first established. As mentioned in previous sections, the fundamental dynamic in defining the problem is the need to determine impact ratios through systematic parameter analysis and guide decision-makers in the pavement type selection process. Accordingly, the flowchart for this study is presented in Figure 3.

4.2. Data and Application

Within the scope of this study, some of the criteria considered in the studies mentioned in the literature section were selected, and some were added by the authors, resulting in the identification of 6 main criteria and 18 sub-criteria. The codes for the identified criteria and sub-criteria are provided in Figure 4. The explanations of the sub-criteria are provided in Table 1.

A survey was conducted using the TOPSIS and AHP methods for the six criteria and 18 sub-criteria identified. The experts were selected based on their professional background in pavement design, construction, and maintenance, and specifically represented public institutions (municipal subsidiaries). Each expert made pairwise comparisons based on the fundamental Saaty scale to ensure the consistency and comparability of the decisions. According to the conceptual framework presented for the study, the survey was first administered to 15 experts. At the end of the survey, 5 out of 15 surveys were found to be inconsistent after two rounds of revised judgments. Hence, the AHP and TOPSIS were conducted using 10 consistent surveys, with the five inconsistent surveys excluded. It is known that survey inconsistencies can sometimes occur due to reasons such as participants' judgments potentially containing uncertainties, the Saaty scale being subjective and non-linear, and the large number of criteria. The distribution of survey participants by their professional experience and the sectors in which they work is presented in Table 2.

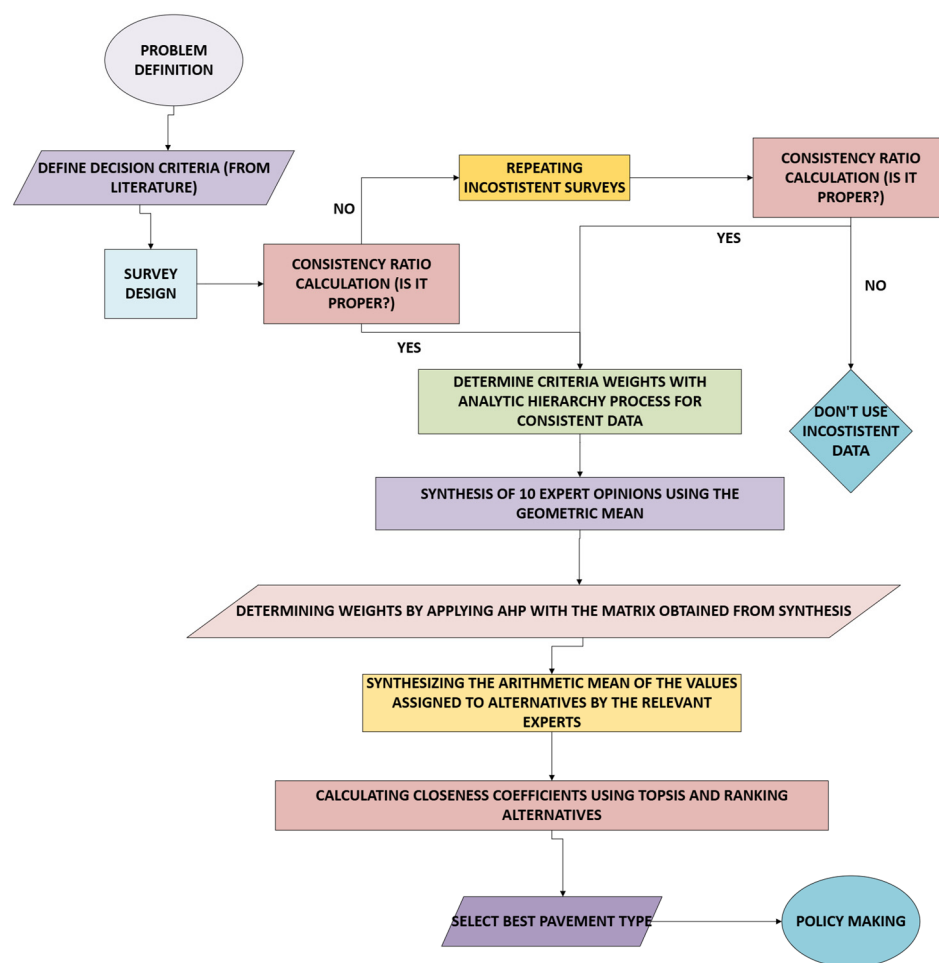


Figure 3. Flowchart of the Study.

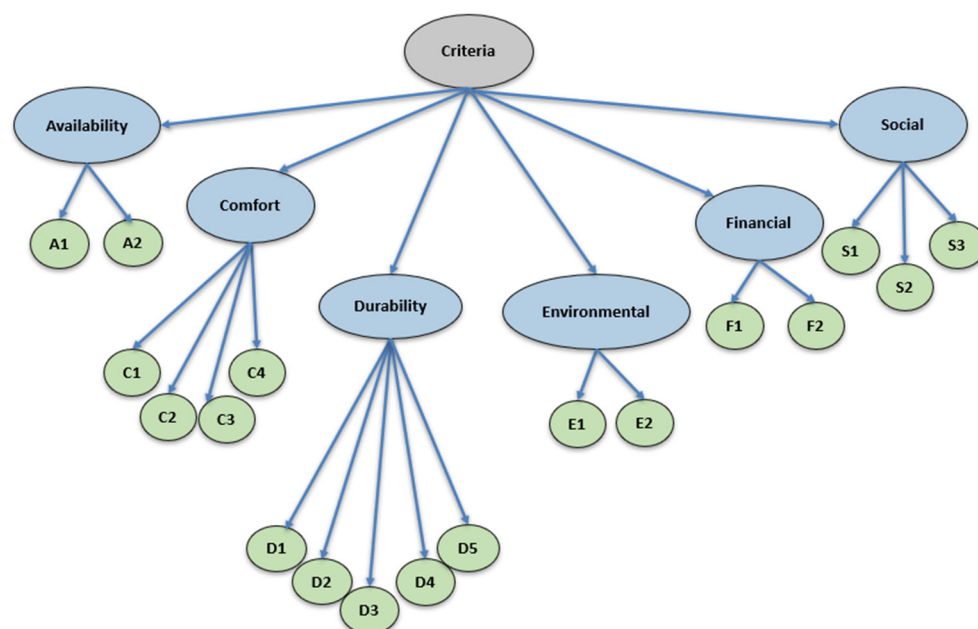


Figure 4. Definitions of Criteria and Sub-Criteria.

Table 1. Explanations of Sub-Criteria.

Code	Explanations
A1	Ease and availability of construction and repair equipment
A2	Ease and availability of construction crew/personnel
C1	Lane visibility
C2	Noise level
C3	Night visibility
C4	Glare from sunlight
D1	Pavement age
D2	Resistance to environmental effects
D3	Resistance to traffic loads
D4	Surface polishing
D5	Shoulder (edge) durability
E1	Recyclability of materials
E2	Eco-friendliness (Environmental Sustainability)
F1	Initial construction cost
F2	Maintenance/Repair cost
S1	Maintenance/Repair frequency
S2	Initial construction time
S3	Service reopening time after maintenance/repair

Table 2. Distribution of Consistent Survey Participants.

ID	Company/Institution Name	Experience in the Sector (Years)	Experience in Transport/Materials (Years)	Position in the Institution
ID1	Istanbul Metropolitan Municipality	12	12	Deputy Director
ID2	Istanbul Metropolitan Municipality	25	25	Regional Director
ID3	Istanbul Metropolitan Municipality	28	4	Engineer
ID4	Istanbul Metropolitan Municipality	13	13	Regional Chief
ID5	Istanbul Metropolitan Municipality	8	5	Regional Chief
ID6	Istanbul Metropolitan Municipality	20	20	Regional Chief
ID7	İston A.Ş.	20	10	Construction Project Manager
ID8	Istanbul Metropolitan Municipality	4	4	Transportation Engineer
ID9	Istanbul Metropolitan Municipality	19	18	Deputy Director
ID10	Istanbul Metropolitan Municipality Road Maintenance Department	9	9	Supervising Engineer

4.3. Analytical Methods

A hybrid method was applied within the scope of this study. The AHP method was used to determine the criteria weights, while the TOPSIS method was used to choose between the two pavement types. Similar AHP–TOPSIS applications in pavement engineering have also been written in recent studies, particularly for preventive maintenance of trunk highways [31] and for evaluating thin asphalt overlays with different material properties [32].

The main reasons for choosing the AHP method in criteria weighing are that AHP converts subjective and individual judgments into a quantitative form, enables high reliability and rational analysis [33], allows for an accordance-based impartial decision-making process, and is therefore free from bias [34], and has the ability to systematically incorporate numerous abstract and concrete criteria into the decision-making process [35]. Furthermore, the reliability it provides to the user through consistency analysis [36] can also be seen as one of these reasons. AHP is a method that has been used for a long time in many fields such as ecology, production and performance management, sustainable development, computer networks, optimization and algorithms, service quality, and risk assessment, and it still retains its relevance [37].

The TOPSIS method, on the other hand, is a method that yields robust results in terms of scalability, speed, and ease of use even in big data contexts [38]. The method is easy to use due to its simple mathematical structure and stands out for its independence from the number of criteria [39]. The TOPSIS method, used in evaluating many issues such as supplier selection, health management, transportation, and infrastructure problems, is known to work quite efficiently with other multi-criteria decision-making methods. The AHP and TOPSIS methods are two methods that complement each other very well [39,40]. This is because while AHP can determine weights, the only subjective element in the TOPSIS method is weights. Particularly in complex selection problems, combining AHP and TOPSIS yields robust performance. Their integrated use completes an objective and transparent decision-making process [40].

The AHP method was developed in the 1970 by Thomas Saaty to solve complex multi-criteria decision-making problems. This technique, which is based on determining the relative importance levels of the criteria, relies on obtaining criteria weights through questionnaires filled out using the 1–9 Saaty scale [41,42]. The importance levels used in this comparison are given in Table 3 [40,43].

Table 3. Importance Levels Used for Comparison [40,43].

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another

Table 3. Cont.

Intensity of Importance	Definition	Explanation
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance is demonstrated in practice
8	Very, very strong	The evidence favoring one activity over another is of the highest possible order of affirmation
9	Extreme importance	
Reciprocals of above	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption

Accordingly, the lowest value is 1/9, the highest value is defined as 9, and the equivalent of equal value is 1 [40,43].

Accordingly, after the possible decision alternatives are determined, the hierarchical structure of the problem is created, binary comparisons of the criteria are made for each hierarchical level and local and global weights of the criteria are calculated [40]. The comparison matrix used to compare n criteria, denoted as $a_1, a_2, \dots, a_n$, according to their relative importance weights is shown in Equation (4).

$$A = [a_{ij}] = \begin{pmatrix} 1 & \dots & a_{1j} & \dots & a_{1n} \\ \vdots & 1 & \vdots & & \vdots \\ 1/a_{ij} & \dots & 1 & \dots & 1/a_{in} \\ \vdots & & \vdots & 1 & \vdots \\ 1/a_{n1} & \dots & a_{nj} & \dots & 1 \end{pmatrix} \quad (1)$$

Accordingly, the values on the diagonal are equal to 1 (since the importance of a criteria with respect to itself is 1). The matrix has a reciprocal property [44].

Each a_{ij} value is normalized, with the aim of scaling them so that the sum equals 1.

$$a'_{ij} = \frac{a_{ij}}{\sum_{k=1}^n a_{kj}} \quad (2)$$

The criteria weights are calculated from the normalized values [45].

$$w_i = \frac{\sum_{k=1}^n a'_{ik}}{n} \quad (3)$$

Then, the consistency index (CI) is calculated:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (4)$$

Here, λ_{max} is the largest eigenvalue of the matrix, and when fully consistent, $\lambda_{max} = n$ and

$CI = 0$. The smaller the CI , the more consistent the decision-maker's responses are. Finally, the consistency ratio (CR) is calculated [40,43,44,46]. While some sources consider a value of 0.2 as tolerable [47], generally, it is expected to be below 0.1 [43].

$$CR = \frac{CI}{RI} \quad (5)$$

Here, the RI mentioned represents the random index for matrices that are randomly generated. The RI values used for different number of elements (n) are provided in Table 4 [46].

Table 4. RI values for different numbers of elements [46].

n	1	2	3	4	5	6	7	8	9	10
Random index (RI)	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Within the scope of the study, after weights were calculated using the AHP method, the TOPSIS method was used to select between pavement types. Developed in 1981 and not involving complex mathematical algorithms, this technique [48] is one of the most widely used multi-criteria decision-making methods. In the TOPSIS method, it is expected that a selected alternative will be close to the ideal solution and far from the negative ideal solution [49]. For example, in Figure 5, in a hypothetical five-alternative system for alternatives A1 and A3, A3's closeness to the ideal solution is a reason for the decision maker to prefer it. In contrast, A1's closeness to the negative ideal solution is a reason not to prefer it [40].

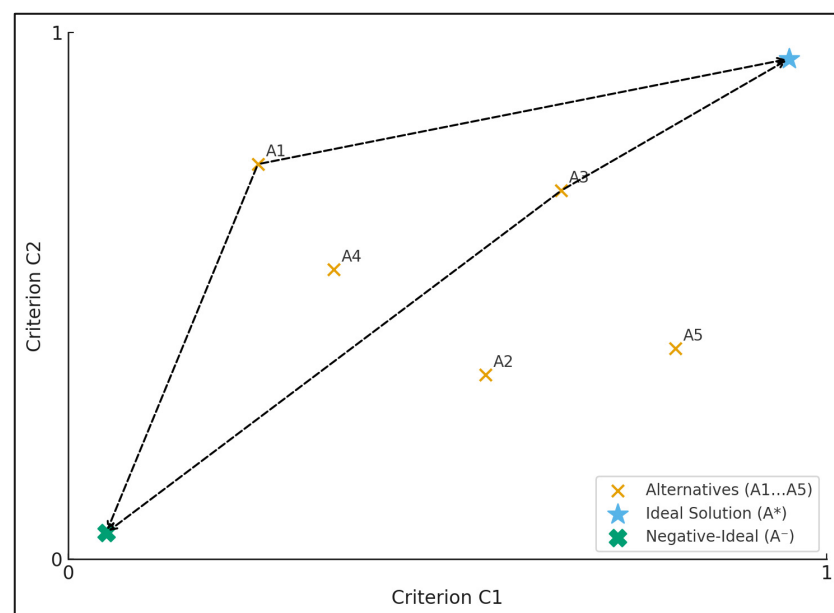


Figure 5. Negative Optimal and Optimal Solutions for Various Alternatives.

The first step in the TOPSIS method is to create the decision matrix. This matrix shows the decision points in the rows and the factors in the columns. It is an $m \times p$ matrix [40].

$$A_{ij} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1p} \\ a_{21} & a_{22} & \dots & a_{2p} \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & \dots & a_{mp} \end{bmatrix} \quad (6)$$

Then, the squares of the values in this matrix are calculated to obtain the column totals of these values, and the normalization process is performed by dividing each a_{ij} value by the square root of the column total [40].

$$n_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^m a_{ij}^2}} (i = 1, \dots, m; j = 1, \dots, p) \quad (7)$$

The normalized matrix obtained is multiplied by the w_i weights obtained from the AHP method, thus yielding the weighted normalized matrix. Let $w_1 \cdot n_{11} = v_{11}$;

$$V = \begin{bmatrix} v_{11} & v_{12} & \dots & v_{1p} \\ v_{21} & v_{22} & \dots & v_{2p} \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ v_{m1} & v_{m2} & \dots & v_{mp} \end{bmatrix} \quad (8)$$

After obtaining the weighted normalized matrix, the maximum and minimum values for each column are found. Depending on the nature of the problem, if a maximization operation is performed, the maximum values become the ideal solution values. In contrast, the minimum values become the negative ideal solution values. In minimization, the opposite is true [40].

Then, the Euclidean distance values for the ideal and negative ideal points are calculated.

$$\text{Ideal distance;} \quad S_i^* = \sum_{j=1}^n (v_{ij} - v_j^*)^2 \quad (9)$$

$$\text{Negative ideal distance;} \quad S_i^- = \sum_{j=1}^n (v_{ij} - v_j^-)^2 \quad (10)$$

Here, v_j^* ve v_j^- are the maximum and minimum values for each column, respectively. There will be S_i^* ve S_i^- for each decision point.

Finally, the relative closeness to the ideal solution (C_i^*) is calculated. This value varies between 0 and 1. $C_i^* = 1$ indicates the absolute closeness of the relevant decision point to the ideal solution, while $C_i^* = 0$ indicates the absolute closeness to the negative ideal solution [40]. Accordingly, in the maximization problem, the alternative with the highest value will be selected.

$$C_i^* = \frac{S_i^-}{S_i^- + S_i^*} \quad (11)$$

5. Results

The consistency rates obtained within the scope of the study and their distribution according to experts are given in Table 5.

Table 5. Consistency scores of the experts.

Experts	Main	Comfort	Durability	Social
ID1	0.097	0.023	0.095	0.033
ID2	0.053	0.000	0.000	0.000
ID3	0.096	0.022	0.068	0.046
ID4	0.098	0.000	0.024	0.016

Table 5. *Cont.*

Experts	Main	Comfort	Durability	Social
ID5	0.087	0.069	0.026	0.000
ID6	0.097	0.069	0.000	0.046
ID7	0.097	0.011	0.062	0.046
ID8	0.059	0.044	0.006	0.000
ID9	0.090	0.017	0.044	0.046
ID10	0.059	0.023	0.004	0.064
Aggregated	0.019	0.000	0.003	0.004

Criteria weights and rankings are given in Table 6. Accordingly, the two most important criteria have been factors related to comfort and finance.

Table 6. Weights and rankings of the main criteria.

Main Criteria	Weights	Rank
Availability	0.1340	5
Comfort	0.2160	1
Durability	0.1341	4
Environmental	0.1868	3
Financial	0.2001	2
Social	0.1289	6

Sub-criteria weights and rankings are provided in Table 7. If an assessment of the sub-criteria is desired, it can be seen that the sub-criteria related to maintenance and repair costs have the highest weight, followed by eco-friendliness, initial construction cost, recyclability of materials, and availability of construction and repair equipment. These are followed by the sub-criteria of night visibility and maintenance repair frequency.

Table 7. Weights and rankings of the sub-criteria.

Sub-Criteria	Sub-Criteria Weights	Overall Weight	Overall Rank
A1	0.5547	0.0743	5
A2	0.4453	0.0597	8
C1	0.2433	0.0526	9
C2	0.1923	0.0415	11
C3	0.3220	0.0696	6
C4	0.2423	0.0523	10
D1	0.1334	0.0179	18
D2	0.2242	0.0301	14
D3	0.2779	0.0373	12

Table 7. Cont.

Sub-Criteria	Sub-Criteria Weights	Overall Weight	Overall Rank
D4	0.1836	0.0246	16
D5	0.1809	0.0243	17
E1	0.4382	0.0819	4
E2	0.5618	0.1050	2
F1	0.4282	0.0857	3
F2	0.5718	0.1144	1
S1	0.4944	0.0637	7
S2	0.2320	0.0299	15
S3	0.2736	0.0353	13

TOPSIS decision matrix is given in Table 8. Average scores for each sub-criterion have been calculated separately for the two alternatives.

Table 8. TOPSIS decision matrix.

Sub-Criteria	Flexible Pavement (Average)	Rigid Pavement (Average)	Ideal Position in TOPSIS
A1	5.6	4.5	Max
A2	6.3	4.1	Max
C1	6.3	4.9	Max
C2	4.8	4.5	Min
C3	4.4	5.5	Max
C4	3.9	4.7	Min
D1	3.1	6.2	Min
D2	3.4	5.7	Max
D3	3.6	6.1	Max
D4	4.2	4.0	Min
D5	3.8	5.2	Max
E1	4.8	3.4	Max
E2	2.1	5.2	Max
F1	4.8	4.0	Min
F2	5.2	3.8	Min
S1	4.7	3.9	Min
S2	5.6	3.5	Min
S3	5.4	3.2	Min

The TOPSIS results obtained after normalization, weighting, and closeness calculations from ideal solutions using the decision matrix are presented in Table 9. According to this, the alternative rigid pavement is the closest to the ideal solution, the farthest from the negative ideal solution, and the closest to a closeness coefficient of 1.

Table 9. TOPSIS results.

Alternatives	S_i^*	S_i^-	C_i^*	Rank
Flexible pavement	0.004851	0.00101	0.172379	2
Rigid pavement	0.00101	0.004851	0.827621	1

6. Discussion

In Turkey, pavement problems have been viewed as issues that should be resolved over time through trial-and-error methods. The main reason for this is that the problems and deficiencies are not clearly defined, and the criteria that could be effective in the solution process cannot be determined systematically and accurately. When explicitly evaluated in terms of pavement applications, the trial-and-error method is seen as a long-term experimental study. Although outputs are more accurate, it is known to be a highly disadvantageous type of application in terms of economic costs and social costs. Therefore, this study evaluates two types of pavements commonly used in Istanbul, a large metropolitan area: flexible and rigid pavements. As a result of questionnaire evaluations and statistical analyses conducted with experts on the subject, it was concluded that criteria related to comfort and costs are the most important. The study revealed that, as expected, comfort was the most critical criterion. Here, it is necessary to elaborate on the comfort criteria. The sub-criteria addressed under the comfort criteria in this study are listed as lane visibility, noise level, night visibility, and glare from sunlight. Therefore, these sub-criteria are not only indicators of comfort but also of road safety. This result reveals that the priority of experts working in the pavement industry for pavement applications is human life, and that when the design is implemented, it is performed primarily according to the minimum safety requirements, with consideration for engineering professional awareness. This situation alone is proof that the choices were made with a rational eye. Suppose an assessment of these sub-criteria is desired. In that case, it can be seen that the sub-criteria examined under the comfort criteria do not rank among the top five sub-criteria. Although night visibility stands out on its own as being more critical than other comfort sub-criteria, the comfort criteria actually becomes the most important criteria when combined with four sub-criteria that do not rank very high. This demonstrates that each sub-criteria is an integral factor for road comfort and safety and that the sub-criteria have been selected very accurately. When evaluated on its own, the night visibility sub-criteria shows actually a very distinctive and clear difference between rigid and flexible pavements, and it is known that night visibility is high in rigid pavements. According to a report conducted by the NSC for 2024, although only a quarter of driving occurs at night, the fact that 50% of fatalities occur at night [50] highlights the importance of pavement being visible at night. When accidents are evaluated in terms of road comfort criteria, a 1997 study by the United Nations Road Traffic Safety Commission [51] determined that road and environmental factors contribute to 28% of traffic accidents, and that the share of roadways in traffic accidents is 30% in the US, 50% in France, and 70% in Russia. It was found that on roads with only a center line and a width not exceeding 22 feet, adding an edge line to increase lane visibility reduced nighttime accident rates by 36% and, in traffic with low visibility, reduced nighttime accidents by 52% [52,53].

Another significant result revealed in the study is that the second most crucial criteria considered when deciding on pavement selection is the financial factor criteria. When an evaluation is made with sub-criteria, it is observed that the two sub-criteria of the financial factor criteria, maintenance repair cost and initial construction cost, are the most critical, 1st and 3rd sub-criteria, respectively. Under today's economic conditions, making an investment decision for an infrastructure project in light of changing technologies is

particularly important because decisions to be made in the social and financial areas must also be accountable, and it imposes a social responsibility on the public for those who will invest [54,55]. The fact that the financial factor criteria is the second most crucial factor in the study reveals that decision-makers are aware of this social burden and make decisions based on the principle of economy, which is the second engineering principle after safety [56]. The increase in maintenance and repair frequency, while being a social sub-criteria ranked 7th, multiplies maintenance and repair costs, thereby increasing cumulative costs. The initial construction cost, as in all projects, emerged in the analysis as one of the factors expected to directly influence the decision-making stage. Budgets allocated to infrastructure investments in Turkey require project managers and policymakers to make decisions on pavement types that meet comfort (and, in fact, safety) requirements while providing services at minimum cost. This situation results in the selection of the available pavement type rather than the preferred pavement type. The most striking statistic in this regard is that 95% of the 68,689 km of state and provincial roads under the responsibility of the General Directorate of Highways in Turkey have been constructed with flexible pavement [57]. Although the study found that rigid pavement is clearly ahead, the most fundamental reason why flexible pavement is still used much more in Turkey—excluding the political context that began in the 1950s—is this availability. This finding indicates that pavement selection practices in Turkey are primarily shaped by availability and habit rather than by performance-oriented decision-making. The fact that the availability of construction and repair equipment sub-criteria is the fifth most crucial sub-criteria also confirms this attitude. When interpreted in the context of Turkey's current infrastructure policies, the importance of financial and environmentally friendly criteria reflects the national priority of focusing on cost efficiency and sustainability principles in transportation planning, and consequently in public investment strategies.

The most striking aspect of the study is that, although they did not rank among the top two criteria in the decision-making process, the sub-criteria of eco-friendliness and material recyclability ranked 2nd and 4th, respectively. This situation demonstrates that the concept of sustainability and environmental responsibility, which is now taken into account in all production processes as required by the times, is also effective in the paving sector, as it is in every industry. Concerns such as the environmental damage caused by large-scale asphalt production processes, their limited lifespan, the abundance of waste material, and the emergence of petroleum-based substances such as bitumen, which are particularly harmful to the environment, both in the production and waste stages, have paved the way for experts to consider the environmental impact of materials in their selection processes.

7. Conclusions

Within the scope of this study, a combined pavement selection process was established for the Istanbul metropolitan area. Accordingly, the combined AHP and TOPSIS method was applied based on the judgments of 10 experts in the field. As a result, 6 criteria and 18 sub-criteria were identified, and importance weights were calculated using the AHP method. The advantageous pavement type was then selected using the TOPSIS method. The analysis provided a clear hierarchy among the evaluated criteria, revealing the underlying logic behind expert decisions. The results revealed that the comfort factor, which is closely linked to safety, and financial factors are two essential components that guide the choice of pavement type. These findings emphasize the value of combining expert insight with systematic MCDM approaches in pavement decision-making. Even if they did not individually rank among the top five sub-criteria, the sub-criteria of lane visibility, night visibility, glare from sunlight, and noise level showed the highest composite weight. In particular, the night visibility sub-criteria emerged as an essential sub-criteria in

the selection of rigid pavements due to the surface brightness and contrast production of rigid pavements.

When considered alongside nighttime accident statistics, this indicates that an accurate sub-criteria selection has been made. The high ranking of the financial factor criteria and its sub-criteria shows that decision-makers are operating within a balance of selection that prioritizes safety while also considering economic factors. Furthermore, it shows that the accessibility criteria guide practical preferences and that the traditional attitude here actually stems from constraints rather than a preference. Another noteworthy result is that, despite not being among the top two main criteria, sustainability criteria are now a fundamental factor rather than a secondary factor in pavement type selection. The fact that the sub-criteria are ranked second and fourth confirms this. These findings have substantial practical and policy implications for transportation authorities and infrastructure planners. All of this necessitates the development of a policy that clearly states night visibility targets in contracts and specifications related to pavement design processes and optimizes them in line with long-term costs within a life cycle approach. The conceptual innovation of the study lies in demonstrating, through a systematic decision-making mechanism, that the comfort criteria is the core of safety and that night visibility provides distinctiveness by showing a clear difference. The methodological innovation demonstrates the measurability of selection behavior using a combined approach. Its political contribution is that it reveals that the fundamental reason for the dominance of flexible pavement in Turkey is not technical superiority but accessibility.

Despite its comprehensive scope, the study has certain limitations. The findings are based on expert opinion and relate to the geographical area of Istanbul. Additionally, different climatic conditions, countries' levels of economic development, and topographical features can significantly alter preferences for pavement types. Therefore, the decision support approach proposed in this study can only be validated through application, particularly in icy continental climate regions, arid climates, countries with varying financial resources and technologies, and geographically constrained topographies. Future studies can reveal how regional, geographical, technological, and socioeconomic contexts shape the priorities of criteria in pavement type selection and how decisions are influenced by comparing the findings obtained under these different conditions. Furthermore, the results can be supported by accident data, geographic measurements, and sustainable material recovery rates, which are topics for future studies. In summary, this study enables highly accountable pavement choices centered on nighttime visibility and supported by an understanding of safety and life cycle.

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Abbreviations

The following abbreviations are used in this manuscript:

NSC	National Safety Council
AHP	Analytic Hierarchy Process
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
MEPDG	Mechanistic–Empirical Pavement Design Guide
SAMDM	South African Mechanistic Pavement Design Method
USA	United States of America
MCDM	Multi-Criteria Decision Making
Csa	Hot-summer Mediterranean climate type
CI	Consistency Index
CR	Consistency Ratio

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