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Novel Application of Pythagorean Fuzzy MCDM in Prioritizing Transportation Alternatives: Insights from Ankara for the Ministry of Transportation

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Abstract

This study underscores the importance of prioritizing transportation modes in Ankara, particularly given the pivotal role transportation holds in contemporary urban societies. Transportation directly shapes the socio-economic framework of metropolitan areas. To address the complexities of transportation in Ankara, the study introduces a hybrid approach by integrating the Fuzzy CRITIC (Criteria Importance Through Inter-Criteria Correlation) method with the novel Pythagorean Fuzzy Weighted Sum Method. This novel approach assesses the various transportation modes available in Ankara, taking into account pivotal criteria such as cost, duration, reliability, comfort, and flexibility. The hybridized methodology offers a systematic way to determine the weights of each criterion. Then, leveraging these weights, the performance of each transportation mode is calculated and ranked. This integrated approach proves to be a powerful analytical tool for addressing multi-criteria decision-making challenges, especially when confronted with uncertainty and intricate details. The outcomes of this research aim to serve as a cornerstone for the Ankara Ministry of Transportation and other key stakeholders. The insights derived can be pivotal for enhancing the existing transportation infrastructure or for the initiation of new, more efficient projects. This study highlights the effectiveness of hybrid decision-making methods for urban transportation, setting a benchmark for similar challenges. It presents a strategic, analytical approach to streamline Ankara's transportation, addressing its complex urban transport needs.

1. Introduction

In today's world, it is evident that transportation plays a critical role in the sustainable development of cities and meeting the needs of communities [1]. With rapidly growing populations, the expansion of city boundaries, and the increasing demand for effective transportation systems to support the daily lives of city residents, the need for efficient transportation is on the rise.

Transportation is a domain where economic, social, and environmental factors intersect, making it crucial to plan and manage transportation systems effectively in a city. Especially in large cities like capitals, they host complex transportation networks. Ankara, as the capital of Turkey, stands out as a prominent example in this regard [2].

In a city sprawled over a vast geographical area like Ankara, residents must have access to a wide variety of transportation options to meet their basic

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needs, such as commuting to work, shopping, and entertainment. Different modes of transportation, including cars, public transit, bicycles, and walking, serve as vehicles for the daily mobility of city dwellers. However, each transportation mode comes with its unique advantages and disadvantages. For instance, individual car usage provides freedom and comfort but may lead to issues like traffic congestion and environmental impacts. Public transportation can reduce costs but may suffer from problems related to timing and reliability. Therefore, effective planning and management of transportation systems in cities become a complex task for decision-makers.

In today's urban landscapes, prioritizing transportation in cities like Ankara is critical for strategic city management. Our study introduces a sophisticated methodology to identify optimal transportation alternatives, combining Fuzzy CRITIC and Pythagorean Fuzzy Weighted Sum for multi-criteria decision-making. This approach comprehensively evaluates various transportation modes in Ankara, focusing on key criteria such as cost, duration, reliability, comfort, and flexibility, to align with the city's evolving needs.

Our research's outcomes not only serve as an analytical guidepost for refining Ankara's transportation strategies but also set a precedent for urban transportation planning in comparable global cities. In essence, this study accentuates the urgency of navigating and refining intricate transportation choices in rapidly expanding urban centers. By doing so, it paves the way for shaping sustainable, cost-effective, and socially cohesive transportation infrastructures that cater to contemporary urban demands.

The structure of this paper is organized as follows: Section 2 delves into an extensive literature review, setting the stage for our research. Section 3 introduces the innovative methodology applied in our study. Following this, Section 4 discusses the specific analytical approaches and techniques used. The paper culminates in Section 5, where we present our key findings, analyze the results, and discuss their implications for urban transportation planning in Ankara.

2. Literature Research

Transportation prioritization and decision-making embodies a structured process wherein cities or regions determine the most apt transportation modes or projects to fulfill their specific mobility needs. This is inherently a multi-criteria endeavor, which necessitates the holistic evaluation of various modes or projects based on designated criteria and objectives.

In the earlier explorations of this field, Çelik et al. [3] embarked on an investigation into the applications of Multi-Criteria Decision Making (MCDM) in the Turkish transportation sector. Their research underscored the efficacy of these methodologies in assessing a plethora of transportation options. Building on this foundational work, Özcan and Celebi [4] employed MCDM methodologies to pinpoint preferred transportation modes throughout Turkey. A subsequent study by Ertugay et al. [5] utilized a fuzzy MCDM approach, emphasizing urban transportation mode preferences in Istanbul and furnishing a systematic ranking of distinct transportation modes. Broadening the scope, Yazdani [6] offered an all-encompassing perspective on the deployment of MCDM methods within transportation systems, thereby elucidating their inherent potential in this realm.

Extending beyond mere transportation, the adaptability of MCDM methodologies in diverse sectors is noteworthy. For instance, Kahraman et al. [7] showcased the versatile nature of these techniques in an array of industries, particularly through their implementation of the fuzzy AHP method for supplier selection. Similarly, underscoring the expansive utility of MCDM, Demirel et al. [8] leveraged the Choquet integral for making decisions on warehouse location. Fast forward to 2021, Zhang et al. [9] accentuated the pivotal role of public transportation within the circular economy. Their innovative study probed into the influence of public participation on mass transit decisions. This was achieved through the integration of fuzzy preference relations and expansive group decision making methodologies. Their approach was distinct, clustering participants using similarity methods and subsequently dissecting decision-making preferences. In 2023, landmark studies continued to build on these foundations. Kraus et al. [10] underscored the importance of sustainable transportation, drawing inspiration from the European Green Deal. Their research introduced a novel methodology based on ISM-P and PROMETHEE, focusing on the evaluation of urban transportation by converging societal, environmental, and economic dimensions. In the same year, Wang et al. [11] proposed an evaluative model for assessing the resilience of urban multi-modal transportation systems (UMTS). Given the escalating complexity of urban growth and transportation networks, this model combined diverse transport modes, such as buses and subways, with simulation and network techniques. A case study in Singapore further solidified the relevance of their proposed indicators.

In this research, we place a magnifying lens on Ankara's transportation dynamics, critically assessing and ranking existing modes using specialized fuzzy methodologies: Fuzzy CRITIC and Pythagorean Fuzzy Weighted Sum. What sets this study apart is its integrated approach, employing a fusion of these methodologies to delve deeper into Ankara's unique transportation milieu. By synergizing Fuzzy CRITIC with the Pythagorean Fuzzy Weighted Sum, our research provides a novel and holistic perspective, standing in contrast to traditional studies that primarily leverage singular methods. The resultant findings underscore not only the alignment with Ankara's distinct transportation necessities but also vouch for the potency of fuzzy methodologies when faced with intricate real-world challenges. In this endeavor, our work emerges as a beacon, offering pivotal insights that could shape strategic interventions in Ankara's urban transportation framework. Summarily, multi-criteria decision-making (MCDM) methodologies are spotlighted as formidable instruments, adept at navigating complex decision-making arenas in transportation and broader sectors.

3. Material and Method

This section delves into the analytical structures and techniques utilized throughout the research. Our study leans heavily on two pivotal methods: the Fuzzy CRITIC and the Pythagorean Fuzzy Weighted Sum. The former, Fuzzy CRITIC, was harnessed for the intricate task of weighting transportation modes, while the latter, Pythagorean Fuzzy Weighted Sum, was designated for computing the aggregate performance scores of the presented alternatives.

The allure of the Fuzzy CRITIC method in the domain of multi-criteria decision-making is primarily its adeptness at navigating the murky waters of uncertainties and nebulous data. Instead of a rigid reliance on precise numerical values, this method champions the use of fuzzy data sets, making it particularly apt for confronting and decoding the ambiguities inherent in real-world scenarios. Such an approach not only acknowledges the inherent uncertainties but also paves the way for generating outcomes that are both resilient and adaptive. This, in turn, arms decision-makers with robust insights, propelling them towards making judicious choices. Meanwhile, the Pythagorean Fuzzy Weighted Sum technique furnishes a coherent and impartial scaffold, adeptly catering to multi-criteria decision-making quandaries shrouded in uncertainties.

3.1. Intuitionistic Fuzzy Set

An Intuitionistic Fuzzy Set (IFS) is an extension of the traditional fuzzy set and is characterized by both a membership function and a non-membership function. Introduced by Atanassov in 1986, the IFS provides a more comprehensive representation for situations where the degree of membership and the degree of non-membership are not always complementary. Specifically, for any element x in a universe of discourse X, an IFS A in X can be represented as shown in Equation 1 [12]:

$$A = \{(x, \mu_A(x), \nu_A(x)) | x \in X\} \quad (1)$$

Where;

- $\mu_A(x)$ is the membership function of x in A.
- $\nu_A(x)$ is the non-membership function of x in A.
- $\mu_A(x) + \nu_A(x) \leq 1$ for every $x \in X$.

3.2. Pythagorean Fuzzy Sets

Pythagorean Fuzzy Sets (PFS) extend the concept of IFS by allowing the sum of the squared membership function and squared non-membership function to be less than or equal to one. This provides a broader scope in expressing uncertainties and is particularly useful in scenarios where there is an inherent hesitation or doubt about the membership of an element. Formally, a PFS A in X can be represented as shown in Equaiton 2 [12]:

$$A = \{(x, \mu_A(x), \nu_A(x)) | x \in X\}$$

with the condition: (2)

- $\mu_A(x)^2 + \nu_A(x)^2 \leq 1$ for every $x \in X$.

The introduction of Pythagorean Fuzzy Sets offers more flexibility in decision-making scenarios, especially in multi-criteria contexts. Zhang and Xu [12] notably extended the traditional TOPSIS method to incorporate the principles of PFS, enhancing the method's applicability to scenarios with vague or imprecise information 1.

3.3. Fuzzy CRITIC Method

Criteria are considered a vital source of information during the decision-making process. Objective weights, termed "objective weights," furnish significant insights to decision-makers. The CRITIC method is utilized to compute the objective weights of criteria considered in multi-attribute decision-making problems. The objective weight derived from this method synthesizes the contrast intensity of each criterion and the discrepancy between criteria. The criterion's contrast intensity is acknowledged as the standard deviation, and the correlation coefficient is employed to calculate the disagreement between criteria [13]. The Fuzzy CRITIC approach is an extended version of the CRITIC method under a fuzzy environment. In this section, this approach has been applied in a Pythagorean fuzzy setting. Pythagorean fuzzy sets, an extension of intuitionistic fuzzy sets, were developed by Yager and are characterized by a membership degree and a non-membership degree, ensuring that the sum of their squares is equal to or less than one. These sets introduce a novel assessment format, especially when depicting a query in the most accurate and realistic manner using both its positive and negative aspects. The steps of the Pythagorean Fuzzy CRITIC method are as follows [14]:

Step 1. Calculation of the degree of uncertainty: For each fuzzy value's degree of uncertainty, where pij (μij, vij) is the Pythagorean fuzzy value for the i.th alternative based on the j.th criterion, The Equation 3 is employed.

$$\Pi_{ij} = \sqrt{1 - \mu_{ij}^2 - v_{ij}^2} \qquad (3)$$

$(i = 1, 2, ..., \mathrm{m}; \mathrm{j} = 1, 2, ..., \mathrm{n})$

and $0 \le (\mu_{ij})^2 + (v_{ij})^2 \le 1$ with the condition

Step 2. Calculation of score functions for each Pythagorean fuzzy value (pij): Using Equation 4, the score functions (R = $(r_{ij})_{m \times n}$) for each fuzzy value are determined.

$$r_{ij} = \mu_{ij}^2 - v_{ij}^2 - \ln(1 + \Pi_{ij}^2) \qquad (4)$$

$(i = 1, 2, ..., \mathrm{m}; \mathrm{j} = 1, 2, ..., \mathrm{n})$

Step 3. Transformation of the R score matrix into an orthonormal Pythagorean fuzzy matrix (Normalization process): The transformation is executed using Equation 5.

$$r_{ij}^{'} = \begin{cases} \dfrac{r_{ij} - r_j^-}{r_j^+ - r_j^-}, & \text{for benefit criteria}, \\[2ex] \dfrac{r_j^+ - r_{ij}}{r_j^+ - r_j^-}, & \text{for cost criteria} \end{cases} \qquad (5)$$

Where; $r_j^- = \min_i r_{ij}$ ve $r_j^+ = \max_i r_{ij}$

Step 4: Calculation of standard deviations for criteria: The calculation is performed using The Equation 6.

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{m} (r_{ij}^{'} - \bar{r}_j)^2}{m}} \qquad (6)$$

Where;

$$\bar{r}_j = \frac{\sum_{i=1}^{m} r_{ij}^{'}}{m} \qquad (7)$$

Step 5: Determination of inter-criterion correlation: The correlation value between the j.th and k.th criterion is computed using Equation 8.

$$\rho_{jk} = \frac{\sum_{i=1}^{m} (r_{ij}^{'} - \bar{r}_j)(r_{ik}^{'} - \bar{r}_k)}{\sqrt{\sum_{i=1}^{m} (r_{ij}^{'} - \bar{r}_j)^2 \sum_{i=1}^{m} (r_{ik}^{'} - \bar{r}_k)^2}} \qquad (8)$$

$(\mathrm{k} = 1, 2, ..., \mathrm{n}; \mathrm{j} = 1, 2, ..., \mathrm{n})$

Step 6: Calculation of the information amount for each criterion: The amount of information is determined using Equation 9.

$$c_j = \sigma_j \sum_{k=1}^{n} (1 - \rho_{jk}) \qquad (9)$$

$(\mathrm{k} = 1, 2, ..., \mathrm{n}; \mathrm{j} = 1, 2, ..., \mathrm{n})$

The larger it is, the more information it contains for a particular criterion, thus the weight of this evaluation criterion is greater than that of the others.

Step 7: Determination of criterion weights: The criterion weights (wj) are ascertained using The Equation 10.

$$w_j = \frac{c_j}{\sum_{j=1}^{n} c_j} \tag{10}$$

$(j = 1, 2, ..., n)$

The Pythagorean Fuzzy Weighted Sum Method is favored in areas requiring intricate decision-making based on uncertain information. This includes supply chain management, engineering design, product development, service quality assessments, and sustainability evaluations.

Decision-making processes often hinge on imprecise and incomplete information. The Pythagorean Fuzzy Weighted Sum Method facilitates a thorough analysis of these uncertainties, empowering decision-makers to make more informed and rational choices. The in-depth analysis provided by this method proves especially advantageous in decision-making scenarios under uncertainty.

3.4. Pythagorean Fuzzy Weighted Sum Method

The Pythagorean Fuzzy Weighted Sum Method was developed to address uncertainties and vague information in MCDM processes. This method amalgamates the traditional weighted sum approach with Pythagorean fuzzy numbers, providing a more holistic analysis. Key features of this method include:

- Flexibility: This method offers a more flexible approach in decision-making scenarios with uncertain information.
- Extensive Analysis: Data limited by conventional methods can undergo a broader analysis using Pythagorean fuzzy numbers.
- User-Friendly: Despite its mathematical foundations, the method remains comprehensible and user-centric in practical applications.

The steps of this method are:

Step 1. Formulation of Decision Matrix: Performance values of alternatives for each criterion, expressed in Pythagorean fuzzy numbers, are compiled into a matrix.

Step 2. Determination of Criterion Importance Levels: Using weights specified by the decision-maker, the relative importance of each criterion in the decision process is defined.

Step 3. Calculation of Weighted Total Scores: The weighted total scores for alternatives are calculated using the criterion weights and Pythagorean fuzzy numbers in the decision matrix as per Equation 11.

$$V(a) = \sum_{j=1}^{n} w_j \times \sqrt{\mu_{ij}^2 + v_{ij}^2} \tag{11}$$

Step 4. Ranking and Selection of Alternatives: Alternatives are ranked based on their calculated weighted total scores. The alternative with the highest score is recognized as the best option.

4. Application

In this section, we will address the application process and outcomes of the study conducted for the Ankara Ministry of Transportation. This study, taking the analysis of data pertaining to the central districts of Ankara as its basis, has been carried out with the aim to more effectively plan and optimize Ankara's transportation systems. The research evaluated six different transportation alternatives, namely "Institutional Shuttle," "Private Vehicle," "Public Transport," "Bicycle/Scooter/Walking," and "Taxi," utilizing the Fuzzy CRITIC and Fuzzy Weighted Sum methods. The decision matrix for each region utilized in this study is provided in Appendix-1. These decision matrices reflect the performance of each alternative in terms of every criterion for the districts of Ankara.

4.1. Data Collection and Analysis

The application process began with the collection of survey data from employees of the Ankara Ministry of Transportation. These surveys assessed six different transportation alternatives for each district of Ankara. Participants evaluated each method based on criteria such as cost, duration, reliability, comfort, and flexibility. To effectively interpret this data, linguistic expressions from respondents were translated into quantifiable measures using Pythagorean Fuzzy Numbers, as illustrated in Table 1.

This conversion was pivotal in processing the gathered survey data using the Fuzzy CRITIC method to obtain a criteria weight matrix. This matrix was instrumental in calculating performance scores. Within this text, Table 2 has been provided, which details the evaluations for the Çankaya district. Additional decision matrices for other districts are presented in Appendix-1. Using the Pythagorean Fuzzy Weighted Sum Method, performance scores were computed, assessing each alternative concerning each criterion, while taking into account the interrelationship between criteria.

4.2. Results and Discussion

When considering the performance scores specific to different regions of Ankara, it is essential to note that each region has its unique needs and priorities. These results indicate how each area evaluates various transportation alternatives and which alternatives they prioritize. The results have been ranked based on the total performance scores of each alternative. This ranking has identified the best alternative according to the given criteria weights. The criteria weights for each district, calculated using the Fuzzy CRITIC method, are provided in Table 3. The performance scores for each district, calculated using the Fuzzy Weighted Total method, are given in Table 4. In Figure 1, transportation preferences across various regions are represented by scores and rankings for each specific mode of transport. The findings are as follows:

Evaluation for Çankaya: The criterion with the highest weight in Çankaya is cost, indicating that residents of Çankaya primarily consider economic factors when determining transportation options. This could be due to Çankaya's central location and potentially higher living costs compared to other districts. The "Bicycle/Scooter/Walking" alternative has received the highest score in Çankaya, suggesting that the district's central location and infrastructure might be suitable for bicycle and scooter usage. However, the "Corporate Service" scored the lowest in this region, hinting that corporate services might not be suited to Çankaya's traffic or infrastructure. One of the critical criteria in Çankaya is the speed and efficiency of transportation.

Evaluation for Keçiören: In Keçiören, cost also has the highest weight, suggesting residents may prefer economically viable transportation options. We can infer that economical options, like public transport, might be frequently used. In Keçiören, while the "Bicycle/Scooter/Walking" alternative ranks first, "Private Vehicle" has the lowest score. The dense population and narrow streets in Keçiören might hinder private vehicle use, advocating for promoting public transportation and bicycle use in this region.

Evaluation for Sincan: The highest weight in Sincan is given to the comfort criterion. This implies that residents of Sincan prioritize comfort and convenience when choosing transportation options. In the Sincan region, "Bicycle/Scooter/Walking" scored the highest, but "Corporate Service" scored the lowest. The vast areas and industrial zones in Sincan might be ideal for bicycle transportation. However, attention should be paid to corporate services' inefficiency in this area.

Evaluation for Etimesgut: For Etimesgut residents, cost is the top priority. This may indicate a preference for economical transportation options. The "Bicycle/Scooter/Walking" alternative has the highest score in Etimesgut. Increasing bike lanes and parking spaces in this area can make transportation more sustainable.

Evaluation for Yenimahalle: In Yenimahalle, cost again has the highest weight. This indicates a preference for economical transportation options. While "Bicycle/Scooter/Walking" ranks first in Yenimahalle, "Taxi" ranks last, pointing to potential traffic congestion, making taxi transportation challenging.

Evaluation for Pursaklar and Altındağ: In both districts, the most important criterion is cost. This suggests a preference for economical transportation options. Both regions have given the highest scores to "Bicycle/Scooter/Walking." Promoting bicycle use in these regions can make transportation more environmentally friendly and economical.

Evaluation for Mamak: In Mamak, the highest weight is on flexibility. This indicates that residents of Mamak value flexibility and accessibility in transportation options. While "Private Vehicle" scored the highest in Mamak, "Taxi" scored the lowest. This hints at Mamak's vast areas being more suitable for private vehicle use.

Evaluation for Gölbaşı: For Gölbaşı residents, cost is the primary concern. This indicates a preference for economical transportation options. "Corporate Service" ranks first in Gölbaşı, whereas "Public Transportation" has the lowest score. The remote location of

Gölbaşı suggests that corporate services might be more effective.

In conclusion, in many districts, the cost criterion emerges prominently. This underscores that Ankara residents lean towards economical transportation options, indicating its significant city-wide importance. Nevertheless, since each district has its dynamics and requirements, transportation planning should be tailored accordingly. For instance, the prominence of flexibility in Mamak might be due to its topography, population density, or other specific conditions. Considering such nuances will aid in devising a more effective and efficient transportation plan. Lastly, tailoring transportation systems by acknowledging the distinct transportation needs and priorities of Ankara's different regions will assist in achieving the city's sustainability objectives. As each area has its unique infrastructure and needs, these results are crucial for developing region-specific transportation solution

Table 1. Linguistic Expressions and Their Equivalents as Pythagorean Fuzzy Numbers

Linguistic Expressions	Pythagorean Fuzzy Number Equivalent
Very High (VH)	(1; 0)
High (H)	(0.8; 0.2)
Medium high (MH)	(0.6; 0.4)
Medium (M)	(0.5; 0.5)
Medium Low (ML)	(0.4; 0.6)
Low (L)	(0.2; 0.8)
Very Low (VL)	(0; 1)

Table 2. Decision matrix of Çankaya region

Region / Criteria	Cost	Time	Security	Comfort	Flexibility
Institutional Shuttle	O	D	Y	O	O
Private Vehicle	O	ÇD	Y	ÇY	ÇY
Public Transport	ÇD	Y	D	D	D
Bicycle/Scooter/Walking	ÇD	Y	ÇD	ÇD	ÇD
Taxi	ÇY	ÇD	O	Y	Y

Table 3. Criteria weights for districts using Fuzzy CRITIC method

Region / Criteria	Cost	Time	Security	Comfort	Flexibility	Total
ÇANKAYA	0,230	0,206	0,218	0,186	0,160	1
KEÇİÖREN	0,250	0,206	0,167	0,209	0,168	1
SİNCAN	0,203	0,216	0,130	0,234	0,217	1
ETİMESGUT	0,307	0,182	0,154	0,178	0,179	1
YENİMAHALLE	0,298	0,155	0,227	0,156	0,164	1
PURSAKLAR	0,279	0,170	0,183	0,203	0,166	1
ALTINDAĞ	0,331	0,143	0,144	0,228	0,154	1
MAMAK	0,178	0,167	0,152	0,248	0,255	1
GÖLBAŞI	0,345	0,150	0,154	0,200	0,151	1

Table 4. Performance scores of districts using Fuzzy Weighted Total method

Region / Alternative	Institutional Shuttle		Private Vehicle		Public Transport		Bicycle/Scooter/Walking		Taxi	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
ÇANKAYA	0,757	5	0,894	2	0,865	4	0,964	1	0,875	3
KEÇİÖREN	0,849	4	0,810	5	0,897	2	0,927	1	0,874	3
SİNCAN	0,746	5	0,756	4	0,785	3	0,801	1	0,792	2
ETİMESGUT	0,818	5	0,887	3	0,869	4	0,969	1	0,888	2
YENİMAHALLE	0,770	3	0,798	2	0,769	4	0,814	1	0,752	5
PURSAKLAR	0,834	4	0,837	3	0,821	5	1,000	1	0,970	2
ALTINDAĞ	0,821	5	0,892	3	0,864	4	0,910	2	0,950	1
MAMAK	0,879	3	0,924	1	0,830	4	0,885	2	0,807	5
GÖLBAŞI	0,870	1	0,828	4	0,725	5	0,867	3	0,868	2

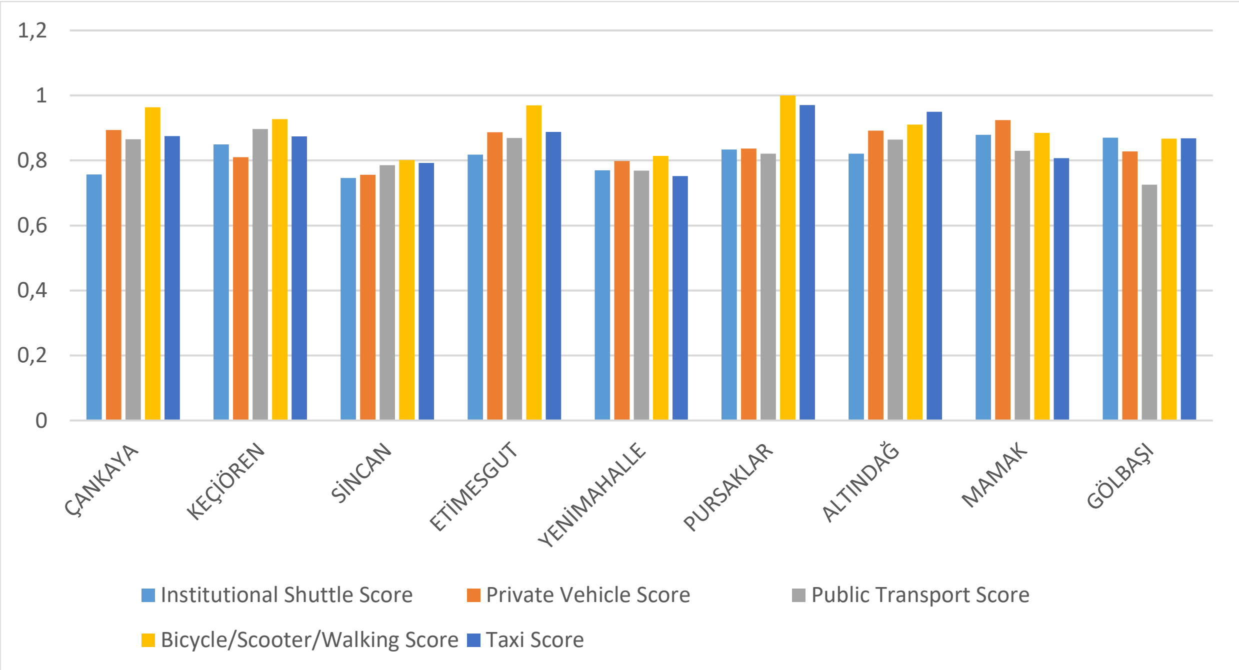

Figure 1. Performance of different transportation types across regions

5. Conclusion and Suggestions

In grappling with sustainable transportation challenges within Ankara's vast urban landscape, our research leveraged advanced fuzzy decision-making methodologies. The adoption of Fuzzy CRITIC and Pythagorean Fuzzy Weighted Sum methods revealed a clear preference for cost-effective transportation across the city, emphasizing the need to balance economic and environmental factors in urban planning. Our findings highlight regional variations in transportation preferences, reflecting the unique infrastructural and demographic characteristics of different districts. For example, the district of Mamak values transportation versatility, indicating a need for flexible transit solutions, while Gölbaşı's remote location shapes its distinct transportation preferences, contrasting with more central areas.

These insights underscore the necessity of customized transportation strategies for each district, considering their specific requirements and challenges. This study not only provides a comprehensive view of Ankara's transportation dynamics but also offers a blueprint for other cities with similar urban structures. Looking forward, the potential to apply these methodologies to cities with diverse landscapes and demographics is immense. Such approaches are crucial in guiding urban centers towards sustainable development, creating environments that balance livability with environmental responsibility.

As we move forward, further research could explore the adaptability of these methods to different urban contexts, potentially offering a versatile toolkit for urban planners globally. Our study sets the stage for a more nuanced understanding of urban transportation planning, advocating for strategies that are both environmentally sustainable and economically viable.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Contributions of the authors

Each aouther has the same contribution to this study.

Statement of Research and Publication Ethics

The study is complied with research and publication ethic

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APPENDIX 1. The decision matrix for each region

Table 5. Decision matrix of Keçiören region

Region / Criteria	Cost	Time	Security	Comfort	Flexibility
Institutional Shuttle	ÇD	O	Y	O	ÇD
Private Vehicle	Y	O	O	Y	ÇY
Public Transport	O	ÇY	ÇD	ÇD	D
Bicycle/Scooter/Walking	O	ÇY	ÇD	ÇD	ÇD
Taxi	ÇY	O	Y	Y	ÇY

Table 6. Decision matrix of Sincan region

Region / Criteria	Cost	Time	Security	Comfort	Flexibility
Institutional Shuttle	D	O	Y	O	O
Private Vehicle	Y	D	O	O	O
Public Transport	O	Y	O	D	D

Bicycle/Scooter/Walking	O	Y	D	D	D
Taxi	ÇY	D	O	O	O

Table 7. Decision matrix of Etimesgut region

Region / Criteria	Cost	Time	Security	Comfort	Flexibility
Institutional Shuttle	ÇD	O	O	O	D
Private Vehicle	Y	D	Y	ÇY	ÇY
Public Transport	D	Y	O	ÇD	ÇD
Bicycle/Scooter/Walking	ÇD	ÇY	ÇD	D	ÇY
Taxi	ÇY	O	D	D	ÇY

Table 8. Decision matrix of Yenimahalle region

Region / Criteria	Cost	Time	Security	Comfort	Flexibility
Institutional Shuttle	O	D	Y	Y	O
Private Vehicle	O	D	Y	ÇY	O
Public Transport	D	O	Y	O	O
Bicycle/Scooter/Walking	ÇD	O	O	O	D
Taxi	O	O	Y	Y	O

Table 9. Decision matrix of Pursaklar region

Region / Criteria	Cost	Time	Security	Comfort	Flexibility
Institutional Shuttle	Y	O	Y	Y	ÇD
Private Vehicle	O	O	Y	ÇY	ÇY
Public Transport	O	Y	Y	Y	ÇY
Bicycle/Scooter/Walking	ÇD	ÇD	ÇD	ÇD	ÇY
Taxi	ÇY	Y	ÇY	ÇY	ÇY

Table 10. Decision matrix of Altındağ region

Region / Criteria	Cost	Time	Security	Comfort	Flexibility
Institutional Shuttle	O	O	ÇY	Y	ÇD
Private Vehicle	Y	Y	Y	ÇY	ÇY
Public Transport	ÇY	Y	Y	D	O

Bicycle/Scooter/Walking	ÇD	Y	D	D	ÇY
Taxi	ÇY	Y	Y	ÇY	ÇY

Table 11. Decision matrix of Mamak region

Region / Criteria	Cost	Time	Security	Comfort	Flexibility
Institutional Shuttle	ÇD	O	ÇY	O	ÇD
Private Vehicle	Y	ÇY	O	ÇY	ÇY
Public Transport	O	ÇY	O	O	ÇY
Bicycle/Scooter/Walking	ÇY	ÇY	D	D	D
Taxi	ÇY	O	D	O	Y

Table 11. Decision matrix of Gölbaşı region

Region / Criteria	Cost	Time	Security	Comfort	Flexibility
Institutional Shuttle	ÇD	O	Y	O	ÇD
Private Vehicle	O	O	Y	ÇY	ÇY
Public Transport	O	Y	O	O	O
Bicycle/Scooter/Walking	ÇD	Y	O	D	Y
Taxi	Y	O	Y	ÇY	ÇY