

Research Article

Integrated MCDM-based evaluation of urban intersection congestion

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ABSTRACT

This study aimed to systematically evaluate the factors affecting traffic congestion at urban intersections and rank them based on congestion levels. Three multi-criteria decision-making (MCDM) techniques—Content validity method (CVM), best-worst method (BWM), and technique for order preference by similarity to ideal solutions (TOPSIS)—were used in an integrated framework. First, 15 potential congestion-related criteria were identified through literature and expert input. Using CVM, 8 key criteria were selected based on field-measured traffic data, official accident records obtained from relevant authorities, and structured on-site observational measurements. Their optimal weights were then calculated via a linear optimization model within the BWM. These weights were fed into TOPSIS for estimation and ranking of junction congestion. The examination also showed the Karayolları intersection to be the most congested (score: 0.711) and Toplu Konut Boulevard Intersection to be the least congested (score: 0.140). The findings provide essential information for decision-makers, aiding initiatives to enhance urban traffic flow by pinpointing crucial crossings and suggesting alternative geometric configurations. In addition, a sensitivity analysis across different weight conditions has confirmed the reliability and practical usefulness of the model. This proposed approach serves also as a tactical tool to prioritize interventions and improve the efficacy of transportation networks in urban environments.

1. Introduction

In view of the rapid urbanization and increase in the population, a rise in vehicle ownership is rapidly realized, especially intensifying traffic congestion in city centers (Tirak, 2019). With the accelerated pace of urbanization, traffic congestion has become a major issue in urban transportation. Intersections are critical nodes that directly influence urban traffic flow and system performance. It is important to accurately analyze intersection congestion so that transportation networks are efficiently used, traffic congestion is reduced, and environmental impacts are minimized. The rapid pace of urbanization, combined with fast-developing technologies, has driven an increase in the number of motor vehicles. As motor vehicles have multiplied, the numbers of traffic accidents and significant damages have similarly increased (Üçer, 2000).

The heavy load on road networks, especially the metropolitan ones, causes traffic jams. Traffic congestion is harmful to both humans and the environment, causing delays, noise from horns and engine sounds, excessive fuel usage in vehicles that are not moving, and deteriorating the environment through air pollution. In addition, the incidence of accidents is enhanced in congested traffic scenarios (Koç, 2010). An urban crossroads is expected to hold sufficient capacity for reliability and alleviating congestion. The junction needs to meet functional criteria in order to achieve these properties (Hatipoğlu et al., 2018).

Existing intersections need to be redesigned to be in line with modern technical conditions and public demand. Especially those junctions on the major thoroughfares of cities, which have become synonymous with

urban character, have become less functional over time. This is not only prone to create weaknesses in everyday urban quality of life and safety, but also to affect negatively the aesthetics as well as the overall quality of the urban area (Oğuzhan, 2015). Thus, as traffic congestion continues to rise, it's the efficient design of intersections and the management of traffic flows that matter. Using geographic information systems (GIS) is useful for identifying traffic flow and analyzing intersections. Using GIS-based analysis, traffic bottlenecks at crossings can be mapped and issue regions can be identified. In addition, GIS serves as an essential tool for scenario modeling, and thus the choice of solutions.

Multi-criteria decision-making (MCDM) methodologies have been increasingly widely used in traffic congestion and intersection efficacy evaluations in recent research. Hao et al. (2017) proposed a holistic approach that assesses traffic congestion, highlighting the significance of decision support systems in urban environments. Alemdar et al. (2021) used a microsimulation-based MCDM method to evaluate intersection performance against multidimensional criteria and provide a comprehensive analytical approach for agencies that enact the approach. Following such investigations, Shan et al. (2021) conducted an urban traffic risk assessment with the technique for order preference by similarity to ideal solutions (TOPSIS) technique, addressing drivers' behavior and road information, which contributed significant insights into safety. Han et al. (2023) used the TOPSIS-based model to evaluate crossings based on their safety ratings utilizing urban road safety indicators. Rankings like these help decision-makers in identifying priority intervention areas in urban transportation planning. Xu and Luo (2023) introduced the following network-based

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evaluation methodology which combined the criteria importance through intercriteria correlation (CRITIC) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methodologies in identifying critical junctions in the urban traffic networks. Pan *et al.* (2021) conducted a comparative analysis of the performance of unusual intersection designs in high-density environments based on the CRITIC method. Such studies have provided evidence of a systematic approach to evaluating factors such as intersection geometry and traffic volume criteria.

Molinari *et al.* (2019) proposed auction-based algorithms for traffic automation at crossings and proposed a combination of these systems to smart transportation approaches and to advanced technology. Lu and Kim (2019) build discrete-time models to control the intersection crossings of autonomous and connected cars, providing solutions to optimize traffic efficiency. Zhang and Cassandras (2018) presented a decentralized control architecture for connected automated cars and found efficient vehicle sequencing at crossings using the proposed system, combining networked automated systems at crossings of vehicles and smart traffic signal control. Chaudhuri *et al.* (2022) performed a comparative study on a range of intelligent traffic signal control algorithms for different scenarios to identify the most efficient control modes for diverse scenarios. Although many of these studies contribute a lot to reducing the traffic congestion around the intersections, the literature is missing the systematic analysis of the existing intersections using several criteria and the development of practical or comparative recommendations for urban transport. This paper applies a holistic evaluative framework, which combines traditional methodologies with multi-criteria decision-making methods, with three main categories: Contingent valuation method (CVM), best-worst method (BWM), and technique for TOPSIS, to better investigate the traffic congestion and intersection efficiency of interlock. The main objective of this framework is to construct a systematic approach to design the rank of crossings according to their traffic congestion. During the first stages, key congestion influencing criteria were identified by expert judgment from the CVM. Subsequently, the criteria were weighted by BWM. In the overall assessment process, the weighted parameters were assessed by TOPSIS to determine which junctions had higher congestion. During this process as a whole, a mix of factors such as daily vehicle count, queue length, accident statistics, and delay times was taken into account. Accordingly, individual proposals of solutions comprising roundabouts, modern roundabouts, pedestrian underpasses/overpasses, and multi-level intersections, were made for every intersection based on the identified ranking in anticipation that such interventions will have significant benefits to decision makers. Hybrid MCDM approaches have been widely employed in transportation studies, particularly combinations such as Analytic Hierarchy Process (AHP) - Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), CRITIC-TOPSIS, and BWM-TOPSIS. These models primarily focus on weighting and ranking stages, often relying on predefined criteria without a formal validation procedure (Jiang *et al.*, 2022). In many cases, criterion selection is based solely on literature review or expert judgment without the application of a quantitative content validation method (Bilişik *et al.*, 2024). In contrast, the proposed framework introduces a structured three-stage integration consisting of CVM for systematic criterion validation, BWM for consistency-controlled weighting, and TOPSIS for alternative ranking. The inclusion of CVM ensures that only statistically validated criteria are incorporated into the decision model, strengthening methodological rigor at the initial stage. Furthermore, BWM provides a more consistent and comparison-efficient weighting mechanism compared to traditional AHP-based approaches (Rezaei, 2015). Another distinguishing aspect of the proposed model is the integration of real-world intersection data with sensitivity analysis and GIS-based spatial visualization (Jiang *et al.*, 2024). While several previous studies rely primarily on simulation outputs or theoretical datasets, this study applies the hybrid framework to observed field data, thereby enhancing practical applicability and decision-making relevance (Maneengam, 2023). Therefore, the novelty of this study lies not merely in combining MCDM techniques, but in structuring them into a validation-weighting-ranking sequence that ensures methodological robustness, operational interpretability, and spatial decision support within urban intersection congestion assessment.

The novelty of this study comes not just from the combination of CVM, BWM, and TOPSIS, but similar integrations have been documented in prior literature. The novelty is the systematic and sequential integration of statistical criterion validation (CVM), consistency-controlled weighting (BWM), and performance-based ranking (TOPSIS) into an integrated analytical framework tailored for urban intersection congestion evaluation. Unlike many previous works relying on set criteria or simulation-based datasets, this research uses field-measured traffic data from real urban intersections in Türkiye. Sensitivity analysis improves the resilience and stability validation of the ranking outcomes across different weight scenarios. The implementation of GIS-based spatial visualization significantly enhances the interpretability and decision-support capability of the framework. The proposed model is not conceived as a hybrid MCDM application, but as a complete, field-validated, and spatially interpretable decision-support system applicable to actual urban traffic management activities.

Meanwhile, fuzzy and uncertainty-based extensions of MCDM methods have become increasingly popular in recent work to address ambiguity in expert evaluations and imprecise traffic data. Amiri *et al.* (2022) proposed a fuzzy tuning of the best-worst method (F-BWM) to enhance the consistency and the reliability of weight estimation under conditions of uncertainty. Ghorabae *et al.* (2018) have proposed hybridizing a fuzzy MCDM model incorporating the sustainability factors in order to enable more flexible assessment in more complex decision making. More recently, Koothongsumrit *et al.* (2024) proposed a unified fuzzy hierarchical risk assessment framework for multimodal transport route selections, which showed the success of uncertainty based MCDM methods during transportation planning activities. Li *et al.* (2026) proposed a TODIM-driven cubic quasiring orthopair fuzzy model that can incorporate entropy and Minkowski distance measures for more complex-group decision-making problems. Rahim *et al.* (2024) introduced p,q,r-spherical fuzzy aggregation operators depending on confidence levels in order to strengthen adaptive management of uncertain and imprecise evaluation environments. Recent works have improved fuzzy MCDM with divergence-based distance measurement in (p, q, r)-spherical fuzzy sets (Khan *et al.*, 2025), and TOPSIS-based nonlinear programming models with cubic p,q-quasiring orthopair fuzzy structures (You *et al.*, 2024), and exponential aggregation operations in a quasiring orthopair fuzzy setting (Rahim *et al.*, 2025). These changes demonstrate the growing tendency of these approaches to support a complex uncertainty-based model of decision making.

However, the present study intentionally employs the classical CVM-BWM-TOPSIS framework to ensure methodological transparency, computational simplicity, and full reproducibility based on crisp expert evaluations. This deliberate methodological choice allows clearer traceability in criterion validation and weighting procedures while maintaining analytical robustness and practical interpretability for real-world urban intersection congestion assessment.

2. Materials and Methods

2.1 Study area

Control at intersections is primarily provided through signalized systems. However, the geometry of an intersection plays a crucial role in establishing an effective signalization system. Within the scope of this study, the district of Atakum in Samsun province was selected as the study area. Atakum is a critical region for urban transportation due to its dense population and increasing traffic activity. As part of the study, nine intersections located between Karayolları Boulevard and Toplu Konut Boulevard were identified for traffic congestion evaluation. These intersections serve as important nodes both for urban traffic management and intercity connectivity. The study area is illustrated in Fig. 1. An aerial drone view of the study area is presented in Fig. 2 (drone image was obtained by the Samsun metropolitan municipality).

2.2 Selection of criteria

The criteria with potential critical impacts on intersections, based on a review of the literature and expert opinions, are listed below.

Vehicle density at the intersection (daily total): Refers to the total number of vehicles passing through all approaches of the intersection within a 24-hour period.

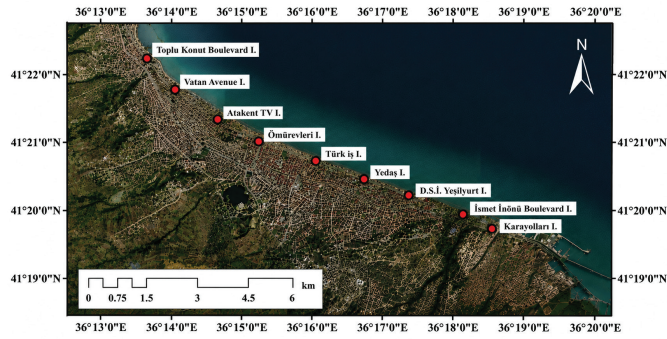


Fig. 1. Study area.



Fig. 2. Drone image of the area containing the intersections.

Number of approaches at the intersection: Indicates the number of road branches meeting at the intersection.

Total number of lanes at the intersection: Represents the sum of lanes on both the main and side roads intersecting at the junction.

Number of traffic accidents Around the intersection: Refers to the number of traffic accidents that occurred within a 100-meter radius of the intersection over the past three years.

Noise level at the intersection: Indicates the hourly noise level generated by vehicles traveling between two intersections. Noise levels were calculated for both decelerating and smoothly moving vehicles. Comparative analyses were conducted to illustrate the differences in noise levels depending on vehicle speed.

Emission levels from vehicles: Refers to the daily amount of emissions released by vehicles traveling between two intersections.

Average queue length at signalized intersections: Denotes the average hourly queue length (in vehicles per signal cycle) formed during red light phases at signalized intersections. In this study, vehicle queues during peak hours were measured as the number of vehicles queuing consecutively within one signal cycle. Three-person teams were deployed at each intersection to ensure simultaneous measurement of queue lengths across all approaches. These measurements were repeated at specific time intervals for each approach, and average values per intersection were calculated. Measurements were primarily conducted between 17:00 and 18:00, which are considered peak hours (Table 1).

Fuel consumption by vehicles traveling between two intersections: This refers to the additional fuel consumed due to deceleration and acceleration at signalized intersections while traveling from one intersection to another.

Average delay time of vehicles at the intersection: The delay experienced by vehicles is measured from a point approximately 150 meters before entering the intersection to a point 150 meters after exiting it. This distance may vary depending on the approach speed to the intersection.

The delay is caused by the waiting time vehicles experience at signalized intersections. The delay time can be defined as the period between when a vehicle begins to decelerate due to traffic signals while traveling at a steady speed and when it regains that original speed after passing through the intersection. Alternatively, it can be described as the time loss experienced between a point approximately 150 meters before entering the intersection and another point 150 meters after exiting it. In this thesis study, delay times were calculated by considering the conditions mentioned above. The measurements were conducted in-vehicle along the study route. A stopwatch was used to measure the time lost due to delays. These measurements were repeated multiple times during peak hours under controlled conditions. The final delay times were determined by calculating the average of these repeated measurements (Table 2).

Examples of the conducted measurements are presented in Figs. 3 and 4.

Number of vehicles entering the intersection approach during peak hours: The number of vehicles entering the leg of the intersection where the tram direction is located during peak hours (per hour). Vehicles entering this leg are moving in the direction of the tram line. This parameter is significant due to the active use of the intersection.

Average distance between the subject intersection and adjacent intersections on the main road : Indicates the proximity of the subject intersection to the previous and next intersections along the main road. The distance between intersections can affect traffic flow and signal coordination.

Number of pedestrians crossing all approaches of the intersection (peak hour average): Represents the number of pedestrians crossing the intersection during the busiest traffic hours (hourly average).

Table 1.
Queue lengths (Cycle/Number of vehicles).

Lane averages	1st lane average			2nd lane average			3rd lane average			Total lane average			Intersection average	Queue length
	Center	Üniversity	Tramway	Center	Üniversity	Tramway	Center	Üniversity	Tramway	Center	Üniversity	Tramway		
Direction intersections														
Karayolları I.	12	47	16	13	49	21	14	52	0	13	49	19	27	
İsmet İnönü Boulevard I.	17	13	3	15	12	2	11	7	0	14	11	3	9	
D.S.İ. Yeşilyurt I.	12	15	2	12	17	3	10	11	2	11	14	2	9	
YEDAŞ I.	17	9	4	16	10	2	14	10	0	16	10	3	10	
Türk- iş I.	8	40	14	8	42	15	7	41	0	8	41	15	21	
Ömürevleri I.	32	11	12	31	12	13	30	10	0	31	11	12	18	
Atakent TV. I.	32	7	10	31	10	0	25	7	0	29	8	10	16	
Vatan Avenue I.	10	6	1	9	6	4	6	3	4	8	5	3	5	
Toplu Konut Boulevard I.	5	6	4	6	6	3	5	4	0	5	5	4	5	

Table 2.
Delay times at intersections (sec).

Intersections	Directions	
	University	Center
Karayolları I.	130	140
İsmet İnönü Boulevard I.	68	78
D.S.İ Yeşilyurt I.	64	76
YEDAŞ I.	62	83
Türk iş I.	80	90
Ömürevleri I.	72	92
Atakent TV. I.	95	80
Vatan Avenue I.	40	41
Toplu Konut Boulevard I.	45	38



Fig. 3. Example of calculations for delay times during travel.



Fig. 4. Example of calculations for delay times during travel 2.

Number of heavy vehicles changing direction at the intersection (daily average): Indicates the daily average number of heavy vehicles entering the intersection from its specific approach and changing direction.

Distance between nearby bus stops and the intersection: Represents the distance between bus stops located near the intersection. This distance is important from the perspective of intersection design and traffic operations.

Number of vehicles parked along the roadside within 150 meters before or after the intersection (during peak hours): Indicates the number of vehicles parked roadside within a 150-meter radius before or after the intersection during peak hours. As this number increases, traffic congestion tends to increase as well.

In order to provide a clearer understanding of how the selected criteria are processed within the proposed analytical framework, the overall methodological flow of the study is summarized below. After identifying the potential criteria and defining their measurement structure, the evaluation proceeds through a structured validation–weighting–ranking sequence. The integrated workflow of the proposed CVM–BWM–TOPSIS framework is presented in Fig. 5.

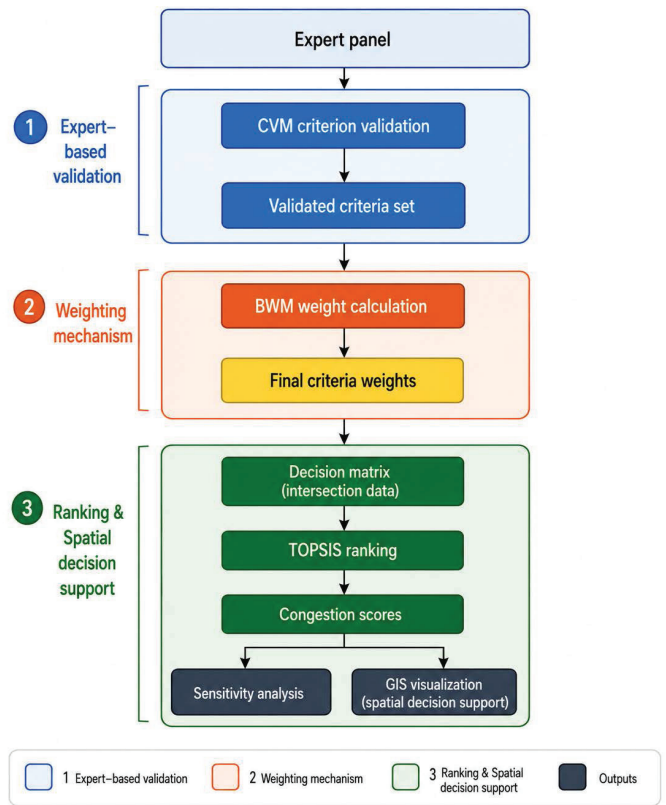


Fig. 5. Integrated workflow of the proposed CVM–BWM–TOPSIS framework.

Fig. 5 illustrates the integrated workflow of the proposed CVM–BWM–TOPSIS framework. The process begins with expert-based CVM, continues with consistency-controlled weighting through BWM, and proceeds to alternative ranking using TOPSIS. Sensitivity analysis and GIS-based visualization are incorporated as supporting stages to enhance robustness and spatial interpretability.

2.3 CVM method

The CVM was originally introduced by Lawshe in 1975 for the purpose of identifying key job performance factors (Dönmez, 2023). It has since become a widely used technique for evaluating the accuracy and applicability of findings, particularly in scale development processes. Content validity analysis plays a critical role in determining the extent to which a study fulfills its intended research objectives. Consistency of results across stages, such as data collection, criterion evaluation, and interpretation, contributes significantly to the reliability of the method. Additionally, the source of this consistency should be clearly explained (Yıldırım & Şimşek, 2008). For CVM to yield valid and reliable outcomes, it is essential that the number of expert participants involved in the assessment process is sufficient. When an adequate number of experts are included, the overall validity level of the developed instrument increases, thereby enhancing the accuracy of the results. Experts are expected to assess each item in the evaluation form in terms of its relevance and appropriateness with respect to the construct being measured (Büyükoztürk, 2005). During the content validity testing process, once the criteria aligned with the research objective are identified, the measurement tool or scale is then constructed accordingly (Yeşilyurt & Çapraz, 2018). Various techniques have been proposed in the literature for assessing content validity. Among these, the method introduced by Lawshe in 1975 remains the most commonly applied approach (Lawshe, 1975).

Ultimately, the primary objective of content validity analysis is to determine the extent to which the items included in the scale reflect the construct being measured. In this context, the scientific rigor of the study is evaluated based on its validity. Experts evaluate each item

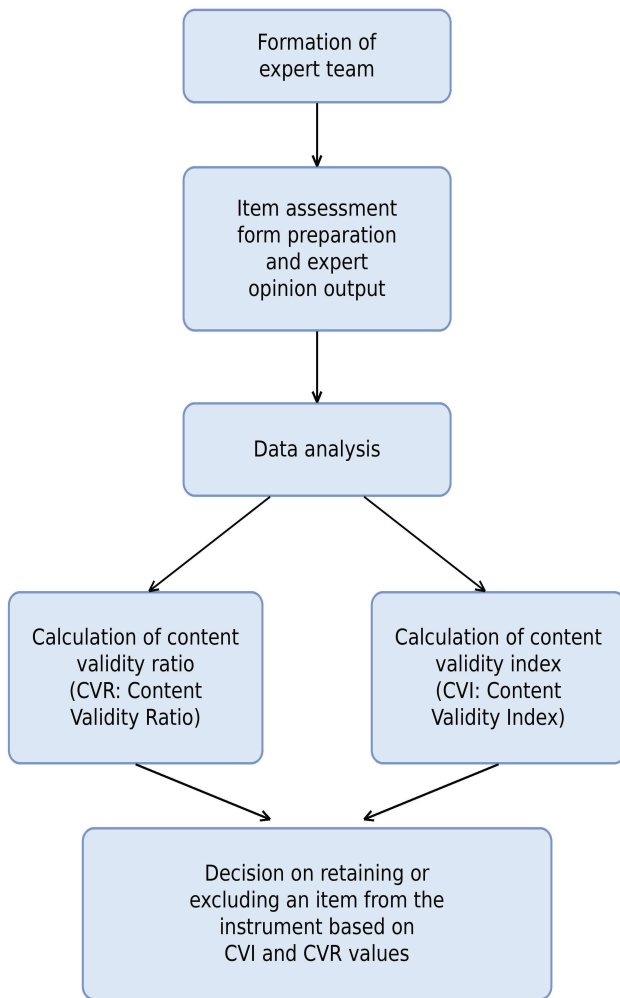


Fig. 6. CVM method workflow diagram.

in terms of whether it serves the intended purpose and adequately measures the relevant construct, thereby making decisions regarding the appropriateness of the items (Büyükoztürk et al., 2016).

In this study, the aim was to identify the importance levels of criteria affecting intersections in order to replace existing intersections in Atatürk Boulevard, Atakum District, Samsun Province, with more efficient road design applications (such as underpasses, overpasses, west exits, multi-level intersections, etc.). The reason for using the CVM method in this study is its simplicity and ease of understanding. The study was conducted according to the workflow diagram presented in Fig. 6.

2.3.1 Formation of the expert group

In order to obtain unbiased results in the calculations conducted for establishing content validity, the qualifications and number of selected experts are highly important. To ensure accurate outcomes from the analyses, a minimum of 5 and a maximum of 40 experts should be selected (Lawshe, 1975; Yeşilyurt & Çapraz, 2018). In this study, a total of 16 experts were selected. The experts were chosen based on their many years of experience in the fields of transportation and road studies. Basic information about the experts is provided in Table 3.

The expert panel was assembled with professionals from a variety but directly relevant fields, including transportation engineering, civil engineering, geomatics engineering, urban and regional planning, and industrial engineering. This interdisciplinary approach was designed to ensure that congestion concerns were evaluated in terms of technology rather than from one specific professional perspective.

Table 3.
General information about the experts.

Demographic variables	Category	Frequency	Percentage (%)
Gender	Man	14	87.5
	Woman	2	12.5
Professional experience (years)	1 -5	5	31.25
	5-10	5	31.25
	10 -15	3	18.75
	15-25	3	18.75
Profession	Transportation engineering	3	18.75
	Industrial engineering	1	6.25
	Geomatics engineering	3	18.75
	Civil engineering	4	25
	Urban and regional planning	2	12.5
	Aircraft maintenance	1	6.25
	Mechatronics engineering	1	6.25
	Computer programming	1	6.25

Although transportation engineers made up a noteworthy part of the panel, due to the research subject, the other experts in planning, geomatics specialists, and other disciplines were also part of the panel, contributing to a full consideration of geometric, operational, spatial, and planning dimensions. This heterogeneity is in agreement with the cross-disciplinary approach towards evaluation, as usually advocated by cross-disciplinary investigation papers on complex urban transportation challenges.

Moreover, all specialized in the field had experience with transportation-related projects, so their assessments reflected practical and technical training. To avoid differential weightings across experts to reduce any disciplinary bias, the importance of expert evaluation was not weighted differently in each expert's views in the CVM and BWM process. This approach supports greater representativeness and methodological rigour in the assessment of junction congestion by the expert panel.

2.3.2 Preparation of the criteria evaluation form and expert opinion results

In this study, expert evaluations were conducted using a method based on Lawshe's (1975) technique. The rating scale consisted of two options: "Appropriate/Retain" and "Not Appropriate/Remove." The study was carried out by utilizing an expert opinion form that included 15 different criteria.

"Appropriate/Retain" = 1

"Not appropriate/Remove" = 0

For example, as all 16 experts evaluated criterion C1 as "Retain," the matrix is formed as shown below.

$$: X_{C1} = [1, 1, 1, 1, \dots, 1]$$

1. Vehicle volume at the intersection (daily total) (C1)
2. Number of intersection arms (C2)
3. Total number of lanes on the main road (both directions) (C3)
4. Number of traffic accidents that occurred around the intersection in the last 3 years (C4)
5. Noise level generated at the intersection (C5)
6. Amount of emissions produced by vehicles (C6)
7. Average queue length around signalized intersections (C7)
8. Amount of fuel consumed by vehicles traveling between two intersections (C8)
9. Average vehicle delay time at the intersection (C9)
10. Number of vehicles entering the intersection arms during peak hours (C10)
11. Distance between the intersection and the preceding or following intersection (C11)

12. Number of pedestrians crossing from all intersection arms (peak hour average) (C12)
13. Number of heavy vehicles changing direction at the intersection (Daily Average) (C13)
14. Distance between nearby public transport stops and the intersection area (C14)
15. Vehicles parked on the roadside within 150 meters before or after the intersection (C15)

In order to present the identified criteria more clearly, each was coded from C1 to C15. Experts were asked to evaluate each of the 15 criteria listed in the form by selecting either "appropriate/retain" or "not appropriate/remove." For the purpose of calculating the content validity ratio (CVR), the responses were scored as 1 for "appropriate/retain" and 0 for "not appropriate/remove." Each criterion was evaluated in terms of the extent to which it serves the intended purpose. Based on the evaluations, experts determined which criteria were essential for assessing workload, drawing on both a review of the relevant literature and the analysis of data obtained in the study (Yeşilyurt & Çapraz, 2018).

2.3.3 Data analysis

In this study, to determine the content validity of the criteria selected for inclusion in the scale, qualitative data obtained from expert evaluations were converted into quantitative data through the calculation of the CVR and content validity index (CVI).

2.3.4 Calculation of CVR

CVR operates based on the formula presented in Eq. 1 (Dönmez, 2023; Ayre & Scally, 2014). In this study, the minimum critical CVR value was determined according to the revised critical values table proposed by Ayre and Scally (2014). For a panel consisting of 16 experts ($N = 16$), the minimum acceptable CVR value is 0.50.

Accordingly, the following decision rule was applied in the evaluation process:

- If $CVR \geq 0.50$, the criterion is considered to possess sufficient content validity and is retained for further analysis.
- If $CVR < 0.50$, the criterion is considered to lack adequate content validity and is therefore excluded from the study.

Since the CVR is calculated as

$$CVR = \frac{n_e - N / 2}{N / 2} \quad (1)$$

where n_e represents the number of experts rating the criterion as "appropriate/retain" and

N represents the total number of experts, and a CVR threshold of 0.50 corresponds to at least 12 out of 16 experts evaluating the item as appropriate. Therefore, only the criteria that received affirmative evaluations from at least 12 experts were retained as valid criteria and included in the subsequent BWM and TOPSIS analyses.

For example, for criterion C2, the number of experts indicating essentiality was $n_e = 15$, while the total number of experts was $N = 16$.

$$CVR_{C2} = \frac{15 - 8}{8} = \frac{7}{8} = 0.875$$

If all experts rate any given criterion on the scale as "Suitable/Retain," the CVR for that criterion will be 1. If more than half of the experts evaluate a given criterion on the scale as "Suitable/Retain," the CVR will take a value between 0 and 0.99. According to the CVR formula, if more than half of the experts indicate "Suitable/Retain," then $CVR > 0$, if exactly half of the experts provide the rating "Suitable/Retain," then $CVR = 0$, and if less than half of the experts express the opinion "Suitable/Retain," then $CVR < 0$. If the CVR ratio is negative or equals zero, it indicates that the criterion in question lacks content

validity. Therefore, items on the scale with such values are directly excluded (Yeşilyurt & Çapraz, 2018; Büyüköztürk et al., 2016). In summary, thanks to CVR, decisions are made regarding which criteria are necessary and whether a criterion is truly suitable for the study. The CVR value varies depending on the number of experts involved in the study. Lowell Schipper calculated these critical values according to specific scales, and Lawshe (1975) used these calculated values to create a table based on the Minimum/Critical values of CVR. Subsequently, certain errors were identified in the table originally developed by Lawshe and the values were recalculated. Ayre and Scally (2014), after examining all these calculations, identified their shortcomings and observed that even a one-person decrease or increase in the number of experts could change the CVR. Based on this finding, they created a new table (Table 1). In this study, the CVR value was determined based on the values provided in the updated table by Ayre and Scally (2014). Table 4 shows that for 16 experts, the critical CVR value is 0.5.

2.3.5 Calculation of the content validity index (CVI)

After determining the criteria to be included in the scale using CVR, CVI is applied to the entire test or measurement tool. The CVI is calculated by taking the average of the CVI values of all the selected criteria. The CVI indicates the extent to which the observed performance range in the test overlaps with the defined functional capacity of a given job performance domain (Yeşilyurt & Çapraz, 2018).

$$CVI = \frac{1}{k} \sum_{i=1}^k CVR_i \quad (2)$$

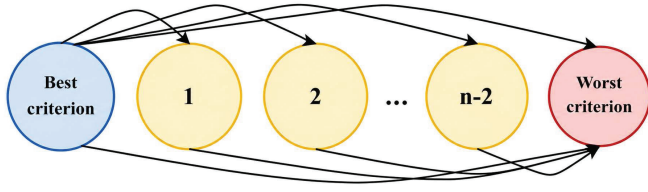
where i denotes the index representing each individual criterion ($i = 1, 2, \dots, k$); CVR_i represents the content validity ratio of the i -th criterion; and k denotes the total number of criteria considered in the analysis ($k = 15$ in this study).

2.4 Best-worst method (BMW)

BWM was first introduced in 2015 by Rezaei as a more efficient alternative to the traditional analytic Hierarchy process (AHP) for solving MCDM problems (Liang et al., 2022; Yıldız, 2022). In this method, weights are determined based on various criteria and alternatives, and final scores are calculated to select the best possible

Table 4.
Minimum/critical values of CVR (Ayre and Scally, 2014).

Expert number	Minimum value	Expert number	Minimum value
5	1.000	23	0.391
6	1.000	24	0.417
7	1.000	25	0.440
8	0.750	26	0.385
9	0.778	27	0.407
10	0.800	28	0.357
11	0.636	29	0.379
12	0.667	30	0.333
13	0.538	31	0.355
14	0.571	32	0.375
15	0.600	33	0.333
16	0.500	34	0.353
17	0.529	35	0.314
18	0.444	36	0.333
19	0.474	37	0.297
20	0.500	38	0.316
21	0.429	39	0.333
22	0.455	40	0.300

Fig. 7. BWM reference comparison (Amiri *et al.*, 2022).

alternative. The way the scoring is conducted and how the comparisons are made are illustrated in Fig. 7 (İşildar, 2018).

It is a method that compares the best (most important) criterion with the others, as well as the worst (least important) criterion with the remaining ones. The aim of this method is to determine the optimal weights of criteria through a simple linear optimization model formed by the comparison system, and to indicate the consistency ratio of the conducted evaluations (Abadi *et al.*, 2018). To ensure more realistic weighting results, experts must be selected from individuals who are knowledgeable and experienced in the relevant field. In this method, experts are asked to select two main criteria from the primary criteria previously determined through the CVM method: the most important and the least important. Then, pairwise comparisons are made between these two reference criteria and the other criteria. As a result of the test, criteria are weighted, and the most suitable alternative is identified. The most significant feature that distinguishes this method from other multi-criteria decision-making methods is that it requires fewer pairwise comparisons, making it simpler, more reliable, and more consistent (Battal Şal, 2021; Mumcu, 2021).

BWM consists of five steps, through which the weights of the criteria are determined (Liang *et al.*, 2022; Battal Şal, 2021)

- 1. Determination of criteria :** Firstly, The set of criteria is defined as $C_1, C_2, C_3, \dots, C_n$.
- 2. Selection of the best and worst criteria:** From the n criteria, experts identify the best (most important) and the worst (least important) criteria.
- 3. Pairwise comparisons :** A scoring scale from 1 to 9 is used for pairwise comparisons:
 - If a criterion has equal importance to another, it is assigned a score of 1.
 - If a criterion is extremely more important, it receives a score of 9.

Experts are asked to compare the best criterion with all other criteria using this scale. Eq. 3 illustrates the comparison of the best criterion with others:verilmiştir.

$$A_B = (a_{B1}, a_{B2}, a_{B3}, \dots, a_{Bn}) \quad (3)$$

Here, a_{Bn} indicates the preference of criterion B over the n -th criterion, which is the most important criterion.

- 4. The pairwise comparison of the least important criterion with the other criteria is also conducted by assigning values within the 1 to 9 scale.** Eq. 4 presents the evaluation of the least important criterion in comparison to the other criteria.

$$A_W = (a_{1W}, a_{2W}, \dots, a_{nW})^T \quad (4)$$

- 5. The optimal weights of the selected criteria are calculated (Eq. 5) (W_1, W_2, W_n).** To assess the consistency of the obtained results, the consistency indicator is examined. If this indicator approaches 0, it indicates a high level of consistency.

$$\left| \frac{w_B}{w_j} - a_{Bj} \right|, \text{ ve } \left| \frac{w_j}{w_W} - a_{jW} \right| \quad (5)$$

The model that minimizes the maximum of the absolute differences for all j is presented in Eq. 6.

$$\min \max_j \left\{ \left| \frac{w_B}{w_j} - a_{Bj} \right|, \left| \frac{w_j}{w_W} - a_{jW} \right| \right\}$$

constraints

$$\sum_j w_j = 1$$

$$w_j > 0 \text{ For all values of } j \quad (6)$$

Eq. 6 can be transformed into a linear form, as shown in Eq. 7.

$$\min \xi$$

$$\left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi \text{ For all values of } j$$

$$\left| \frac{w_j}{w_W} - a_{jW} \right| \leq \xi \text{ For all values of } j \quad (7)$$

$$\sum_j w_j = 1$$

$$W_j > 0 \text{ For all values of } j$$

After all these steps are carried out, the weights of the criteria and the consistency index ξ are calculated. The index ξ is defined as the consistency ratio of the comparison system. The consistency ratio is determined according to Eq. 8.

$$\text{Consistency Ratio} = \frac{\xi}{\text{Consistency Index}} \quad (8)$$

The closer this ratio approaches 0, the higher the consistency. Conversely, as it approaches 1, the lower the level of consistency (Liang *et al.*, 2022; Battal Şal, 2021) (Table 5).

Aggregation of individual expert weights

After solving the BWM linear optimization model separately for each of the 16 experts, individual weight vectors were obtained. Each expert k produced a weight vector expressed as (Eq. 9):

$$w_j^{(k)} = w_1^{(k)}, w_2^{(k)}, w_3^{(k)}, \dots, w_n^{(k)} \quad (9)$$

Where $w_j^{(k)}$ represents the weight assigned to criterion j by expert k , and n denotes the total number of criteria.

To derive a single consensus weight set for use in the TOPSIS analysis, the geometric mean method was applied. For each criterion j , the aggregated weight was calculated as (Eq. 10):

$$w_j = \left(\prod_{k=1}^m w_j^{(k)} \right)^{\frac{1}{m}} \quad (10)$$

where m denotes the total number of experts ($m = 16$).

Since the geometric mean values do not necessarily sum to one, a normalization procedure was subsequently applied to ensure that the

final weights satisfy the condition $\sum_{j=1}^n w_j = 1$. The normalized final weights were calculated as (Eq. 11):

Table 5.
Consistency index (CI).

α_{Bw}	1	2	3	4	5	6	7	8	9
Consistency Index (max ξ)	0	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Table 6.
Decision matrix (Akyüz et al., 2011).

Alternatives	Criteria		
	y_1	y_2	y_k
a_1	y_{11}	y_{12}	y_{1k}
a_2	y_{21}	y_{22}	y_{2k}
a_3	y_{31}	y_{32}	y_{3k}
$\vdots$	$\vdots$	$\vdots$	$\vdots$
a_n	y_{n1}	y_{n2}	y_{nk}

$$w_j = \frac{w_j}{\sum_{j=1}^n w_j} \quad (11)$$

The resulting normalized weights were then used in the TOPSIS-based intersection ranking process.

2.5 TOPSIS method

The TOPSIS method is one of the most well-known multi-criteria decision-making techniques. It was initially introduced by Hwang and Yoon (1981) and later extended into a more comprehensive framework by Yoon (1987). The core principle of this method is to identify both the positive and negative ideal solutions. The selected alternative should have the shortest distance to the positive ideal solution (Nadaban et al., 2016). The negative ideal solution, on the other hand, minimizes the benefit criteria while maximizing the cost criteria. The most suitable alternative is identified as the option exhibiting the minimum distance to the positive ideal solution and the maximum distance from the negative ideal solution (Akyüz et al., 2011). Through the TOPSIS method, alternatives are compared based on predefined criteria and within the minimum and maximum value ranges of those criteria, according to their proximity to the ideal situation (Yurdakul and İc, 2003). The application of the TOPSIS method involves seven procedural steps, as outlined below (de Farias Aires and Ferreira, 2019; Akyüz et al., 2011; Yurdakul and İc, 2003).

Step 1: Firstly; The decision matrix is constructed (Table 6). After obtaining the alternatives to be evaluated and their corresponding weight coefficients, the decision matrix is formed in matrix format. In the decision matrix, the alternatives (a_1, a_2, a_n) are listed vertically.

A_n : Possible alternatives
 y_k : Criteria related to alternative performance, where $k = 1$ to n
 (y_{1k}, y_{nk}) : Values indicating the performance rating of each alternative with respect to the corresponding criterion

Step 2: Normalization of the decision matrix

In this step, the decision matrix is normalized by taking the square root of the sum of the squares of the criterion values in the matrix. This process ensures that all criteria are brought to a common scale, eliminating any unit-based discrepancies. The normalization procedure is illustrated in Eq. (12) (Yurdakul ve İc, 2003).

$$Z_{ij} = \frac{y_{ij}}{\sqrt{\sum_{j=1}^n y_{ij}^2}} \quad i = 1, 2, \dots, n; j = 1, 2, \dots, k \quad (12)$$

Table 7.
Rating scale.

Criterion evaluation	Numerical value
Extremely low importance	0
Very low importance	1
Low importance	3
Medium importance	5
High importance	7
Very high importance	9
Extreme importance	10

Step 3: Weighting of the normalized decision matrix

The elements of the normalized decision matrix are weighted according to the importance assigned to each criterion. In the weighting process, the normalized version of the 1–10 rating scale is used (Table 7). This step is illustrated in Eqs. 13 and 14 (Yurdakul ve İc, 2003).

$$X_{ij} = w_j \cdot z_{ij} \quad i = 1, \dots, n; j = 1, \dots, k \quad (w_j; \text{the weight of each } j\text{-th criterion}) \quad (13)$$

$$V = \begin{bmatrix} V_{11} & V_{12} & \dots & V_{1j} & \dots & V_{1n} & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ V_{i1} & V_{i2} & \dots & V_{ij} & \dots & V_{in} & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ V_{m1} & V_{m2} & \dots & V_{mj} & \dots & V_{mn} & \dots \end{bmatrix} \quad (14)$$

Step 4. Definition of the positive and negative ideal solutions (a^+ and a^-):

In this step, for each column of the weighted matrix, the maximum and minimum values are determined (Eqs. 15 and 16).

$$a^+ = \{x_1^*, x_2^*, \dots, x_k^*\} \quad (\text{maximum values}) \quad (15)$$

$$a^- = \{x_1^-, x_2^-, \dots, x_k^-\} \quad (\text{minimum values}) \quad (16)$$

Step 5: The maximum distance to the ideal solution is calculated according to Eq. 17.

$$S_i^+ = \sum_{j=1}^k (x_{ij} - x_j^*)^2 \quad i = 1, \dots, n \quad (17)$$

Step 6: The minimum distance to the ideal solution is calculated according to Eq. 18.

$$S_i^- = \sum_{j=1}^k (x_{ij} - x_j^-)^2 \quad i = 1, \dots, n \quad (18)$$

Step 7: The score of each alternative and its corresponding ranking are calculated according to the formula given in Eq. 19.

$$C_i^* = S_i^- / S_i^+ \quad 0 \leq C_i^* \leq 1 \quad i = 1, \dots, n \quad (19)$$

In this study, the aim is to rank the densities of intersections using the TOPSIS method. Based on the calculations performed through all these steps, the intersections are ranked according to their density levels. Within this framework, evaluations were conducted based on eight accepted criteria.

All computational procedures employed in this paper are defined accordingly through equations and logical arguments and the inclusion of well chosen decision criteria. CVR and CVI were calculated using the expert evaluation matrix that was based on binary (0–1) responses. For each of the experts, the BWM linear optimization model was solved, and the final weight vectors were combined using the geometric mean, and normalized. The TOPSIS method also consisted of the choice matrix preparation, vector normalization, ideal solution identification, and distance computation as per the formulas described in the methodology section. Computations were performed in Microsoft Excel. Thus, the observations made in this research are fully replicable with the same datasets and expert judgments.

Therefore, the framework ensures a stepwise conceptually structured advancement from criteria validation (CVI) through weight determination (BWM) and at last to alternative ranking (TOPSIS), thus minimizing methodological fragmentation among stages.

2.5.1 Sensitivity analysis

MCDM methods are commonly used to address complex decision problems, and the reliability of their outcomes is closely related to their sensitivity to changes in input parameters (Bakır and Atalık, 2021). One

Table 8.

Main criteria identified based on the CVM method.

Expert No	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Participant 1	1	1	1	1	0	0	1	0	1	1	1	0	0	0	1
Participant 2	1	1	1	1	0	0	1	0	1	1	1	1	0	1	1
Participant 3	1	1	1	1	0	1	1	0	1	1	0	1	1	1	0
Participant 4	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
Participant 5	1	1	1	1	0	0	1	0	1	1	0	0	1	0	0
Participant 6	1	1	1	1	0	0	1	0	1	1	1	1	1	0	0
Participant 7	1	0	1	1	0	0	1	0	1	1	1	1	1	1	1
Participant 8	1	1	1	1	0	0	1	0	1	1	1	0	1	0	0
Participant 9	1	1	1	1	0	0	1	0	1	1	1	0	1	1	1
Participant 10	1	1	1	1	0	0	1	0	1	1	1	0	1	0	0
Participant 11	1	1	1	1	0	0	1	0	1	1	1	1	1	1	0
Participant 12	1	1	0	0	1	1	1	0	1	1	1	1	0	0	1
Participant 13	1	1	1	1	0	0	1	0	1	1	1	1	0	1	1
Participant 14	1	1	1	0	0	0	1	0	1	1	1	0	1	0	0
Participant 15	1	1	1	1	0	0	1	0	1	1	0	0	0	0	1
Participant 16	1	1	0	1	0	0	1	0	1	1	1	1	0	0	0
Not relevant/To be removed	0	1	2	2	15	13	0	15	0	0	3	7	6	9	8
Relevant/To be retained	16	15	14	14	1	3	16	1	16	16	13	9	10	7	8
Content validity ratio	1.0	0.875	0.75	0.75	-0.875	-0.625	1.0	-0.875	1.0	1.0	0.625	0.125	0.25	-0.125	0.0
Content validity index	0.325														

effective way to assess this reliability is through sensitivity analysis. Sensitivity analysis tests the robustness of the solution against changes in the criteria weights.

In this study, various weight scenarios were developed to examine how sensitive the resulting rankings are to changes in the criteria weights. Each scenario represents a different decision-making situation by assigning different weights to the criteria.

3. Results and Discussion

In this section, 15 criteria were determined based on a literature review and expert opinions. The criteria with CVR values greater than 0 were selected as the main criteria. Among the identified criteria, eight were determined as the main criteria using the CVM method (Table 8).

The scale-level CVI was calculated by averaging the CVR values of all items in the initial item pool, rather than only the retained criteria. This approach provides an overall assessment of the content validity of the entire scale. Accordingly, the obtained CVI value (0.325) reflects the general content validity level of the full set of proposed criteria prior to elimination.

As a result of the analysis conducted using the CVM method, 8 out of 15 criteria were selected. The selected criteria are presented below.

1. Vehicle density at the intersection (daily total) (C1)
2. Number of legs at the intersection (C2)
3. Total number of lanes on the main road (both directions) (C3)
4. Number of traffic accidents around the intersection in the last three years (C4)
5. Average queue length at signalized intersections (C7)
6. Average vehicle delay time at the intersection (C9)
7. Number of vehicles entering the intersection arms during peak hours (C10)
8. Distance between the intersection and the adjacent upstream or downstream intersection (C11)

The eight main criteria determined via the CVM method were adopted as the fundamental indicators for assessing intersection density. Subsequently, BWM was employed to establish the relative significance levels of these criteria. As a result of the BWM evaluation process,

Table 9.

Criteria weights by decision makers and final aggregated weights ((Geometric mean – normalized)).

Participants	C1	C2	C3	C4	C7	C9	C10	C11	Consistency ratio
Participant 1	0.08	0.10	0.13	0.06	0.19	0.08	0.33	0.05	0.30
Participant 2	0.10	0.07	0.08	0.06	0.20	0.13	0.33	0.04	0.14
Participant 3	0.25	0.07	0.07	0.09	0.25	0.14	0.09	0.04	0.20
Participant 4	0.22	0.05	0.04	0.22	0.09	0.13	0.22	0.03	0.19
Participant 5	0.29	0.08	0.08	0.07	0.17	0.17	0.11	0.04	0.20
Participant 6	0.26	0.16	0.10	0.08	0.06	0.05	0.26	0.03	0.21
Participant 7	0.26	0.06	0.06	0.08	0.15	0.10	0.26	0.04	0.20
Participant 8	0.32	0.13	0.10	0.04	0.10	0.08	0.19	0.06	0.21
Participant 9	0.22	0.09	0.09	0.13	0.16	0.13	0.13	0.04	0.25
Participant 10	0.32	0.08	0.04	0.06	0.13	0.07	0.20	0.10	0.23
Participant 11	0.20	0.08	0.06	0.20	0.11	0.11	0.20	0.04	0.20
Participant 12	0.26	0.04	0.10	0.15	0.07	0.07	0.26	0.06	0.20
Participant 13	0.10	0.13	0.08	0.06	0.33	0.20	0.07	0.04	0.21
Participant 14	0.30	0.18	0.12	0.07	0.12	0.09	0.09	0.05	0.20
Participant 15	0.15	0.26	0.26	0.05	0.08	0.04	0.10	0.06	0.20
Participant 16	0.27	0.11	0.05	0.04	0.23	0.16	0.08	0.06	0.19
Geo. Mean	0.21	0.09	0.08	0.08	0.14	0.10	0.16	0.05	0.21

individual decision-maker weights and the final aggregated criterion weights calculated using the geometric mean are displayed in Table 9.

The intersections with calculated weights were ranked in terms of density using the TOPSIS method. First, the values of the criteria for each intersection were presented in the decision matrix shown in Table 10.

Subsequently, each criterion was normalized by dividing it by the square root of the sum of squares, as shown in Table 11.

The positive-ideal (a^+) and negative-ideal (a^-) solutions, representing the best and worst performance values, respectively, were identified from the weighted "D" matrix, as shown in Table 12.

Table 10.
Decision matrix of criteria values across intersections.

Intersections▼	Criteria							
	C1	C2	C3	C4	C7	C9	C10	C11
Karayolları I.	70270	4	8	4	27	135	698	0.8
İsmet İnönü Boulevard I.	63300	3	8	9	9	73	496	0.8
D.S.İ. Yeşilyurt I.	55013	4	9	7	9	70	444	0.7
YEDAŞ I.	60521	4	8	5	10	73	626	0.8
Türk- iş I.	61197	4	8	11	21	85	852	1.1
Ömürevleri I.	64407	4	8	5	18	82	964	1.1
Atakent TV. I.	52460	3	7	5	16	88	418	1.1
Vatan Avenue I.	46679	3	9	7	5	40	676	1
Toplu Konut Boulevard I.	49760	4	8	7	5	42	440	0.8

Table 11.
Normalization of the decision matrix.

Intersections▼	Criteria							
	C1	C2	C3	C4	C7	C9	C10	C11
Karayolları I.	0.4	0.36	0.33	0.19	0.6	0.56	0.36	0.28
İsmet İnönü Boulevard I.	0.36	0.27	0.33	0.43	0.2	0.3	0.25	0.3
D.S.İ. Yeşilyurt I.	0.31	0.36	0.37	0.33	0.2	0.29	0.23	0.26
YEDAŞ I.	0.34	0.36	0.33	0.24	0.22	0.3	0.32	0.27
Türk- iş I.	0.35	0.36	0.33	0.52	0.46	0.35	0.44	0.38
Ömürevleri I.	0.37	0.36	0.33	0.24	0.4	0.34	0.49	0.41
Atakent TV. I.	0.3	0.27	0.29	0.24	0.35	0.36	0.21	0.4
Vatan Avenue I.	0.27	0.27	0.37	0.33	0.11	0.17	0.35	0.37
Toplu Konut Boulevard I.	0.28	0.36	0.33	0.11	0.11	0.17	0.23	0.3

Table 12.
Determination of ideal values using the weighted "D" matrix.

D=	C1	C2	C3	C4	C7	C9	C10	C11
	0.08	0.03	0.03	0.015	0.08	0.055	0.06	0.013
	0.07	0.03	0.03	0.033	0.03	0.03	0.04	0.014
	0.06	0.03	0.03	0.026	0.03	0.029	0.04	0.012
	0.07	0.03	0.03	0.019	0.03	0.03	0.05	0.012
	0.07	0.03	0.03	0.041	0.06	0.035	0.07	0.018
	0.08	0.03	0.03	0.019	0.05	0.034	0.08	0.019
	0.06	0.03	0.02	0.019	0.05	0.036	0.03	0.018
	0.06	0.03	0.03	0.026	0.02	0.016	0.06	0.017
	0.06	0.03	0.03	0.026	0.02	0.017	0.04	0.014
a ⁺ =	0.08	0.03	0.03	0.041	0.08	0.055	0.08	0.019
a ⁻ =	0.06	0.03	0.02	0.015	0.02	0.016	0.03	0.012

Table 13.
S⁺ ve S⁻ values.

S ⁺	0.035	0.073	0.078	0.069	0.031	0.042	0.067	0.087	0.092
S ⁻	0.085	0.033	0.025	0.033	0.071	0.067	0.04	0.026	0.015

In the final step, the distances to the positive-ideal (S⁺) and negative-ideal (S⁻) solutions were computed (Table 13). Using these distance measures, the performance scores and the final density-based rankings of the intersections were established (Table 14).

According to Table 14, the Karayolları intersection was determined to be the most congested, whereas the Toplu Konut Boulevard intersection exhibited the lowest level of congestion. This ranking was derived

Table 14.
Density-based rankings of intersections.

Intersections▼	Score	Density-based rankings
Karayolları I.	0.711	1
İsmet İnönü Boulevard I.	0.314	6
D.S.İ. Yeşilyurt I.	0.244	7
YEDAŞ I.	0.322	5
Türk- iş I.	0.696	2
Ömürevleri I.	0.613	3
Atakent TV. I.	0.372	4
Vatan Avenue I.	0.227	8
Toplu Konut Boulevard I.	0.140	9

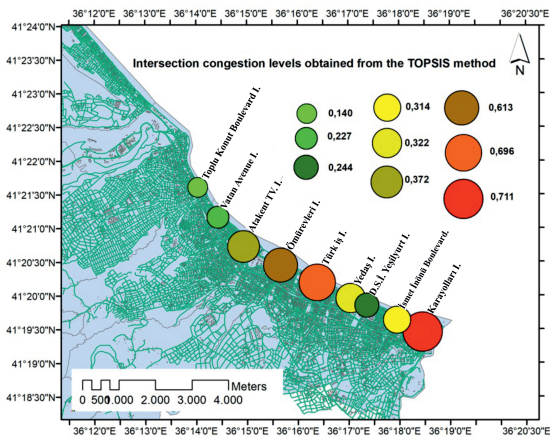


Fig. 8. Representation of intersection density rankings based on the TOPSIS method.

from a holistic assessment of all criteria, analyzed and prioritized using the CVM and BWM methodologies. The resulting intersection density rankings were visualized by mapping them within a GIS environment (Fig. 8).

Specifically, this research used GIS mainly for the spatial representation of intersection congestion rankings derived from the TOPSIS algorithm. Intersection locations were presented as point features in a GIS environment, and attribute data for each intersection were provided along with matching TOPSIS scores and ranking values. Based on congestion scores, the intersections were represented to create a thematic map depicting the spatial distribution of congestion levels.

While GIS was not used in the CVM-BWM-TOPSIS computational processes, it was systematically integrated as a post-analytical spatial decision-support component of the framework. After congestion ratings were obtained, the crossings' spatial coordinates were integrated into the GIS environment for thematic mapping and spatial patterns analysis. This integration allows for quantitative and geographical assessment of congestion severity, which can support area-based prioritization and strategic urban transportation planning.

The ranking obtained as a result of the TOPSIS method was finally evaluated through a sensitivity analysis to verify its consistency.

To perform the sensitivity analysis, simulated weight criteria were generated, and the potential effects of changes in the weight coefficients on the ranking of alternatives were examined. For this purpose, eight simulated weight sets were created (Ghorabae et al., 2018). Through these simulated weight scenarios, a total of eight different TOPSIS rankings were obtained. The generated weight scenarios are presented in Table 15.

The results of the sensitivity analysis based on the weight scenarios presented in Table 15 are presented in Fig. 9.

The analysis of the results revealed that in 7 out of 8 scenarios, there were no significant deviations from the original rankings.

Table 15.
Sensitivity analysis weight scenarios.

Scenarios▼	C1	C2	C3	C4	C7	C9	C10	C11
Scenario1	0.0278	0.0556	0.0833	0.1111	0.1389	0.1667	0.1944	0.2222
Scenario 2	0.0556	0.0833	0.1111	0.1389	0.1667	0.1944	0.2222	0.0278
Scenario 3	0.0833	0.1111	0.1389	0.1667	0.1944	0.2222	0.0278	0.0556
Scenario 4	0.1111	0.1389	0.1667	0.1944	0.2222	0.0278	0.0556	0.0833
Scenario 5	0.1389	0.1667	0.1944	0.2222	0.0278	0.0556	0.0833	0.1111
Scenario 6	0.1667	0.1944	0.2222	0.0278	0.0556	0.0833	0.1111	0.1389
Scenario 7	0.1944	0.2222	0.0278	0.0556	0.0833	0.1111	0.1389	0.1667
Scenario 8	0.2222	0.0278	0.0556	0.0833	0.1111	0.1389	0.1667	0.1944

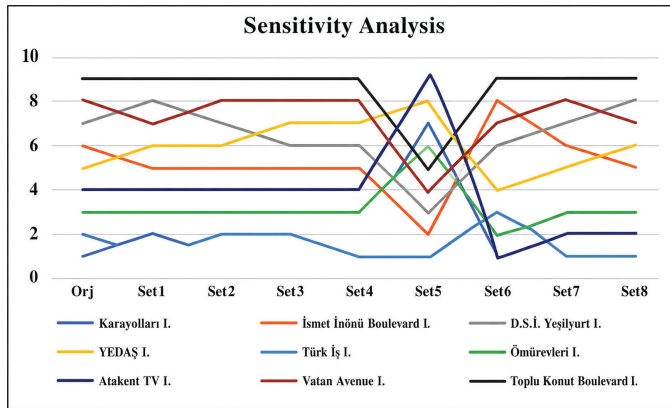


Fig. 9. Outcomes of the sensitivity analysis.

This indicates that the ranking obtained through the TOPSIS method remains valid across different weighting scenarios. However, as can also be seen in Fig. 8, significant deviations from the original ranking were observed only in Scenario 5. When the weighting set of Scenario 5 is analyzed, it is evident that the criterion 'average queue length accumulated around signalized intersections' (C7), which was identified as one of the most important criteria according to the BWM method, received the lowest weight in this scenario. Additionally, in this scenario, 'the number of traffic accidents occurring around the intersection in the last three years' (C4) and 'the total number of lanes (both directions) on the main road' (C3) were assigned the highest weights. It is also clear that (C7) exhibits a wider range of observed values compared to other criteria. All of these factors contributed to the significant deviation from the original rankings observed in this scenario.

For Scenario 5, the large difference can be explained by analyzing the dispersion characteristics of the criteria. Of all eight criteria, average wait length (C7) showed one of the widest fluctuation ranges across junctions. Under the TOPSIS paradigm, criteria with greater dispersion usually have a greater impact on the differentiation between alternatives after normalization. Therefore, with regards to the weight of C7, when viewed from the previous BWM results, the ranking scheme becomes increasingly sensitive based on congestion severity, as shown in the queue build-up.

In Scenario 5, C7 was purposely ranked at a lower weight, and some of the criteria with relatively lower variability (number of traffic accidents (C4) and total number of lanes (C3)) were given a high weight. The restrictions on the flexibility of those criteria also reduced the diversity of alternatives and changed the rank structure.

In conclusion, queue length was shown as a highly discriminative and performance-sensitive measure from the decision framework, and one that is more accurate when assessing operational congestion. However, as per the sensitivity detected in Scenario 5, where C7 appears to play a crucial role in the embedded CVM-BWM-TOPSIS system, the lack of variability in which the model is loaded is a result of a sensitivity test without a potential weakness (not instability).

Table 16.
Proposed redesign alternatives and indicative construction cost ranges.

Intersections	Proposed design alternative	Indicative construction cost range (€)
Karayolları intersection	Multi-level intersection	3.000.000 €
İsmet İnönü Boulevard intersection	Trumpet intersection	2.500.000 €
D.S.İ. Yeşilyurt intersection	Modern roundabout intersection	30.000 €
YEDAŞ intersection	Modern roundabout intersection	30.000 €
Türk iş intersection	Underpass intersection	3.000.000 €
Ömürevleri intersection	Underpass intersection	3.000.000 €
Atakent TV. intersection	Trumpet intersection	2.500.000 €
Vatan Avenue intersection	Pedestrian overpass	200.000 €
Toplu Konut Boulevard intersection	Pedestrian overpass	200.000 €

Total estimated cost: approximately €15,000,000

The sensitivity analysis supports the structural contribution of the queue length to the ranking model, but its actual application implies determining the cost-effectiveness of the proposed redesign solutions. As a result, in addition to congestion-based prioritizing, a preliminary cost assessment is conducted to estimate the projected financial costs of the proposed intersection redesign options. The proposed design solutions and their respective estimated construction budgets are listed in Table 16. Such estimates allow policy-makers to evaluate priorities for reducing congestion by budget considerations. Although a thorough cost-benefit analysis goes beyond what is assessed in this work, the information offered represents a first assessment of feasibility for infrastructure planning.

The indicative construction costs were estimated at an order-of-magnitude level based on comparable previously implemented infrastructure projects, publicly available municipal investment data, and current unit-price schedules (Koç, 2010; Kayseri Metropolitan Municipality, 2019; Ankara Metropolitan Municipality, 2021; Ayvaz, 2023). The values are provided solely for preliminary feasibility assessment. Land acquisition, utility relocation, geotechnical improvements, and detailed engineering design costs are not included. Therefore, the presented Figures should be interpreted as indicative estimates rather than definitive project budgets.

4. Conclusions

This study aims to assess and prioritize traffic congestion at urban intersections through the application of MCDM techniques. In this context, a total of 15 evaluation criteria were initially identified based on a comprehensive review of the relevant literature and expert consultations. These criteria were selected to reflect the principal factors contributing to congestion at signalized intersections. To ensure the validity and relevance of the selected criteria, the CVM was employed. The CVM analysis resulted in the identification of 8 core criteria that were determined to have a significant impact on congestion formation. These validated criteria were subsequently subjected to a weighting process using the BWM, which enabled a systematic and expert-informed quantification of each criterion's relative importance. According to the BWM results, Criterion K1 was found to have the highest weight, while Criterion K11 was assigned the lowest. The resulting weights were incorporated into the TOPSIS, allowing for an objective ranking of intersections based on their congestion intensity. The analysis revealed substantial variations in congestion levels across the studied intersections. Specifically, the Karayolları Intersection obtained the highest congestion score (0.711), whereas the Toplu Konut Boulevard intersection recorded the lowest score (0.140).

The main objective of this study is to provide a scientifically-based evaluation framework for decision-makers and urban planners in managing traffic congestion at intersections. The combined use of multi-criteria decision-making methods enables the consideration of

multiple factors affecting the entire system, rather than relying on a single indicator. This approach facilitates a systematic analysis of traffic issues at intersections and supports the identification of priorities for effective solutions.

In conclusion, restructuring traffic management policies—particularly through improvement measures at high-density intersections—plays a crucial role in more efficient traffic flow management. The methodological framework applied in this study is adaptable to similar problems in different cities and can serve as a guide for decision-makers in developing sustainable transportation policies.

Although the proposed method was applied to nine intersections in Samsun province, the methodology also contains something that can easily be adapted to larger datasets. The CVM stage is dependent only on the number of criteria and is not sensitive to the volume of intersections. BWM weighting methodology relies on the comparisons of criteria, and is not affected by the number of alternatives evaluated. In the TOPSIS phase, a larger number of intersections leads to more compute and the calculation of distances can then be performed in proportion to the number of intersections. However, these systems rely on traditional matrix computations and can be well performed, even for several intersections, using widely accessible analytical tools.

As a result, the proposed CVM-BWM-TOPSIS arrangement remains agnostic to structural requirements and is amenable to a general adoption to bigger urban areas. With increased crossings, its computational design retains effectiveness while remaining relevant in extensive metropolitan transportation systems.

The proposed framework provides not only practical guidance for the sustainable practice of urban traffic management, but also a feasible methodology for scale-up. The combined CVM-BWM-TOPSIS method enables top-down prioritization of intersection solutions, and the local authorities to determine where the most traffic congestion is, and prioritize constrained construction assets more effectively. Sustainable traffic management, therefore, makes both a geometric design and planning cooperation, including transportation authorities, urban development agencies, municipal planners, and traffic safety units necessary. As a result, stakeholder involvement should be integrated into the decision-making process, particularly in the selection and implementation of major infrastructure projects. A recommended approach potentially may encourage participatory planning through the integration of expert assessments through the use of publicly available performance indicators as tools for enhancing transparency and institutional accountability. The results suggest a stratified intervention approach: low cost interventions such as new roundabouts and pedestrian overpasses can deliver short- to medium-term sustainable effects, whilst grade-separated interchanges are long-term strategic investments. This approach to prioritization increases financial viability and operational efficiency in urban traffic systems in order to achieve operational sustainability.

In addition, reductions in fuel consumption, vehicle operating expenditures, and congestion environmental impacts may yield medium-term economic benefits. Similar to traffic conditions, such improvements may recover the implementation costs within a brief timeframe. Future research can broaden the proposed system to various multi-city comparisons to examine its applicability to different urban and cultural settings. In addition, fuzzy extensions of the BWM may also increase the model's capability to handle the ambiguity in expert evaluations. Comparative studies using other weighing methods, for example, AHP or CRITIC, might further enhance the robustness of the proposed decision framework. However, besides the methodological variations, the flexibility of the proposed framework for different urban environments should be noted as well. The approach has been designed to be locally adaptable architecturally to other locations, but its implementation may vary based on the particular situation and context. In this context, a key issue has to do with data. In some settlements, reliable traffic counts, accident statistics, and wait duration measurements may not be systematically collected or made public. In data scarce contexts, implementation of this concept may require using proxy indications, short traffic checks, or simplified performance metrics. The cultural and urban dynamics can heavily influence congestion dynamics and infrastructure priorities. Variations in urban topography (grid vs radial designs), public transport dependency,

characteristics of mode distribution, informal traffic practices, and regional driving culture could affect the importance of factor selection for decision-making. Safety indicators may be prioritized in metropolitan locations with significant pedestrian traffic, and in busy and fast motorizing cities the most important indicators are capacity. Accordingly, the relative weights of criteria according to the CVM-BWM-TOPSIS procedure are not evenly distributed but depend on the context. Generalisability of the framework to other metropolitan areas requires a recalibration of criteria weights through consultation with local experts and empirical validation in order to enhance contextual appropriateness in such decisions and harden the decision results. In addition to its current methodological framework, expanded future extensions could expand the analytical power of the present system. Future investigations could use fuzzy extensions of MCDM models to better handle the uncertainty and linguistic ambiguity in the expert assessments. As traffic measurements are not static variables, combining traffic sensors with intelligent transportation system (ITS) inputs will provide an updated congestion assessment dynamically. Moreover, linking the CVM-BWM-TOPSIS framework with microscopic or macroscopic traffic simulation solutions would also allow some types of traffic simulation models to generate prediction scenarios and assist planners to analyze potential implications of traffic conditions of different intersections under various intersection configurations to make decisions before they are implemented. Such methodological assimilation would also improve flexibility, prediction accuracy, and the strategic relevance of the framework in a complex urban mobility system.

CRediT authorship contribution statement

Aziz Uğur TONA: Conceptualization, methodology, investigation, writing – original draft, writing – review & editing, visualization.
Erdem Emin MARAŞ: Conceptualization, methodology, investigation, writing – original draft, writing – review & editing, visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of generative AI and AI-assisted technologies in the writing process

AI-assisted language tools were used solely for improving grammar, language clarity, and readability of the manuscript. The scientific content, methodology, data analysis, and interpretation of results were developed entirely by the authors. No AI tool was used for data generation, analysis, or decision-making processes.

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