A Multi-Criteria Decision-Making Approach for Hazmat Transportation

Zafer Yilmaz and Vedat Verter

Abstract Hazardous materials (hazmat) transportation is a niche segment of the transport industry, whereby the cargo imposes risk on the public health, the environment, and the property. A plethora of methodologies have been developed to find optimal routes for hazmat vehicles, which consider hazmat accident risk, population exposure, and cost. While everyone recognizes the relevance of these factors, we are unaware of studies that do not take into consideration all the factors together.

In this study, we consider three main factors, and nine sub-factors together for hazmat transportation and propose a practical methodology to find optimal routes. First, we propose finding the factor weights using AHP methodology. In our case study based in Istanbul, Turkey, where we elicited the views of eight international experts on hazmat transportation, the most important main and sub-factors are found as "Consequences" and "Population exposure," respectively. Next, we propose finding the arcs one composite score for each arc on a road network by combining the data at the sub-factor level using TOPSIS methodology and factor weights found in the first step. Finally, optimal routes between origin–destination (OD) pairs can be identified using ArcGIS network analysis tool, in which total route score is minimized. We compare the optimal routes found using our methodology and the methods used in previous studies. The results are encouraging from the perspective of practical applicability of the three-step procedure we propose in this chapter.

Keywords ArcGIS · AHP · Hazardous Materials Transportation · Multi-Criteria Decision-Making · TOPSIS

Z. Yilmaz (✉)
Business Administration Department, TED University, Kolej Çankaya – Ankara, Turkey
e-mail: zafer.yilmaz@tedu.edu.tr

V. Verter
Supply Chain Management Department, Michigan State University, East Lansing, MI, USA
e-mail: verter@broad.msu.edu

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1 Introduction

Hazardous materials (hazmat) transportation constitutes a niche segment of the transport sector due to the risk caused by dangerous goods carried. If a hazmat accident causes an explosion or hazmat release, its consequences (fatalities, injuries, and property–environment damages) are often more spectacular than an ordinary traffic accident. Therefore, hazmat accidents are accepted as "low risk high consequence" events. For example, 2700 fatalities were reported in 1982 due to a gasoline truck explosion in a tunnel in Afghanistan. A train incident in Quebec/Canada caused 47 fatalities in 2013 and hence the responsible company Irving Oil has been ordered to pay $four million. Considering the possibility of significant loss of human life and cost, no one dares to neglect the very low incident risks on road segments while estimating the hazmat risk of a road segment. The hazmat risk on a road segment is associated with the past hazmat accidents data in traditional hazmat transportation models.

There are two primary stakeholders in hazmat transportation: the *regulators* (legal authorities) who try to decrease the risk on the population, property, and environment by determining the available links on the road network of hazmat transportation, and the *carriers* who focus on cost minimization by entailing routing decisions (Kara & Verter, 2004). The average travel cost for a hazmat vehicle is around $ 250 per hour including the estimated hourly fuel cost (Verma & Verter, 2010). 2.5 billion tons of hazmat were shipped in the USA in 2012 (Ditta et al., 2019), which cost billions of dollars. To increase the buy-in from industry, the transportation cost needs to be a central concern, since any solution causing travel time extensions or delays will cause important amount of cost increases. The prevailing research show that there are three most important factors that affect hazmat transportation decisions:

- Hazmat transportation risk due to hazmat accidents causing explosion or hazmat release.
- Transportation cost (driver cost, travel cost of the hazmat vehicle, etc.).
- Consequences (fatalities, injuries, property and environmental damage, evacuation or clean-up costs, etc.).

Most of the hazmat transportation studies focus on hazmat risk assessment, routing, scheduling, and consequences analyses (Yilmaz et al., 2016). As we discuss in more detail in the next section, while some of the researchers only focus on finding optimal solutions with respect to the hazmat transportation risk, there are also some researchers who propose bi-objective solutions by both considering risk and cost. Some researchers only focus on the consequences since the hazmat accident probabilities are too low and consequences are too high. Recent studies focus on value-at-risk models since consequences involve dramatic losses although the probability of a hazmat accident is too low. Complex mathematical models are developed and exact or heuristic solution procedures are proposed. It is often hard to implement these complex methods in practice, when the decision maker does not have deep methodology knowledge. In addition, we are not aware of any prevailing studies, which focus on *all relevant factors* together in proposing solutions for hazmat transportation.

In this study, in an effort to fulfill the gap mentioned above, we develop a methodology based on multi-criteria decision-making approach, which can be easily used in hazmat transportation practice. Our methodology consists of three steps. First, we determine the *criteria* (factors) that affect hazmat transportation and find their weights using Analytic Hierarchy Process (AHP) methodology. Next, the road segments (arcs) are conceived as *alternatives* and the scores for the road segments are obtained using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methodology, which combines the data of all factors into one unique score for each road segment by also including the criteria weights found in the first step. Finally, those scores for the road segments are imported and adopted to be used in ArcGIS network analysis tool and optimal routes between origin destination (OD) pairs are found in which the scores of road segments are minimized. Hence, the proposed methodology includes all the factors together and gives practical solutions for hazmat transportation problems. We present a Case Study in Istanbul, Turkey to find the optimal routes for hazmat vehicles in order to show the efficiency of the proposed methodology.

The organization of the chapter is as follows. The next section describes the key literature on which this chapter has been developed. The methodology for the proposed model is defined in the third section. The case study is presented, and its findings are highlighted in Sect. 4. We conclude with a discussion in Sect. 5 and the opportunities for future research in Sect. 6.

2 Literature Review

There are many studies that focus on different aspects of hazmat transportation in the literature. Despite very low incident risks, hazmat transportation has been a very popular topic in many studies due to the value at risk. Different kinds of hazmat transportation related topics can be found in the literature nevertheless the most popular ones are risk assessment and routing. Erkut and Verter (1998) define the traditional risk as the risk of transporting hazmat B over a unit road segment A (such as a one mile stretch) and they formulate the risk as the multiplication of p_{AB} and *CAB* where p_{AB} = probability of an incident on the unit road segment A for hazmat B, and *CAB* is population along the unit road segment A within the neighborhood associated with hazmat B. They claim that estimates of incident probabilities are between 0.1 and 0.8 per million miles. Later studies focus on *CAB* and they extend the definition of *CAB* by including cost of damage on nature, evacuation cost, property damage cost, etc. However, the risk p_{AB} is always considered same which is named as traditional hazmat risk.

Hazmat accidents are considered as low probability high consequences events. Kang et al. (2014) propose value at risk model to generate route choices for a hazmat shipment based on a specified risk confidence level. Toumazis and Kwon (2015), in their paper, apply an advanced risk measure, called conditional value-at-risk (CVaR), for routing hazmat trucks which offers a flexible, risk-averse, and computationally tractable routing method that is appropriate for hazmat accident mitigation strategies.

Kang et al. (2014) summarize the risk assessment formulas in different studies as follows (For all min $l \in$P);

Expected risk: $\sum_{(i,j)} \in A^l\ p_{ij}C_{ij}$
Incident consequence: $\sum_{(i,j)} \in A^l\ C_{ij}$
Incident probability: $\sum_{(i,j)} \in A^l\ p_{ij}$
Perceived risk: $\sum_{(i,j)} \in A^l\ p_{ij}\ (C_{ij})^q$
Mean-variance: $\sum_{(i,j)} \in A^l\ (p_{ij}C_{ij} + kp_{ij}\ (C_{ij})^2)$
Disutility: $\sum_{(i,j)} \in A^l\ p_{ij}(\exp(kC_{ij} - 1))$
Maximum risk: $\max_{(i,j)} \in A^l\ C_{ij}$
Minimax (Uncertain probabilities): $\min_w \max_p \sum_{(i,j)} \in A^l\ w_{ij}\ (p_{ij}C_{ij} + c_{ij})$
Conditional probability, $\sum_{(i,j)} \in A^l\ p_{ij}C_{ij} \sum_{(i,j)} \in A^l\ p_{ij}$

where l is the number of links, p_{ij} is accident probability on link $(i, j) \in A$, c_{ij} is cost on the link $(i, j) \in A$, C_{ij} is accident consequence on the link $(i, j) \in$A, A is the number of road segments, P is the set of available paths for shipment s.

The studies summarized above focus on accident risk, the consequences, and sometimes both. Relatively in all studies, the incident risk remains constant along an arc which is p_{ij}: accident probability on arc (i, j).

In some of the researches, in addition to focusing on hazmat risk assessment and consequences, cost is also included. Kara and Verter (2004) find bi-level solutions by considering both risk and travel costs on road segments to meet the carriers' travel cost concerns. The literature surveys; Erkut et al. (2007), Yilmaz et al. (2016), and Ditta et al. (2019) are advised for detailed information about hazmat transportation risk assessment studies.

Eventually, hazmat accident risk, consequences, and costs are the main factors on a road segment that researchers concentrate on. The researchers propose very complex algorithms to find optimal or heuristic solutions while finding the best routes between OD pairs. They usually develop complex math models and use some solvers (i.e., GAMS and CPLEX) to find the optimal routes. In most of the studies, as it is summarized by Kang et al. (2014), multiplication of hazmat risk and possible consequences or either only hazmat risk or consequences are minimized in the objective functions of the math models.

In this study, we believe that the factors that affect the hazmat transportation decisions (i.e., risk, consequences, and cost) will have different weights on the decisions that should be taken into consideration while finding optimal routes. So, AHP methodology is used in our study to find the weights of the main and sub-factors. The experts who work on hazmat transportation and published articles in Web of Science indexed journals are asked to fill out a questionnaire. Their replies are analyzed by using AHP methodology in order to find the importance weights of the factors. Next, the road segments are conceived as alternatives in TOPSIS methodology and the risk, cost and consequences related data for each alternative (road segment) are combined into one score for each alternative by using TOPSIS methodology. Finally, ArcGIS network analysis tool which uses Dijkstra algorithm is used to find optimal routes between OD pairs in which the scores obtained in TOPSIS methodology are minimized. The details of the methodology are given in the next section.

There are a very limited number of hazmat transportation related studies in which multi-criteria decision-making methodologies (i.e., AHP and TOPSIS) are included. For example, Sattayaprasert et al. (2008) propose a method to create a risk-based network for hazmat logistics by route prioritization with AHP. This research has been conducted with the information of short-range freight transportation mainly for gasoline movement and for a specific case and location only. The researchers define main and sub-criteria and high-medium and low-level risks for those criteria. Our study differs from this research since in addition to the criteria proposed in Sattayaprasert et al.'s (2008) research, we include hazmat vehicles and other types of vehicle accident risks in our main and sub-criteria. The other difference is that we assign scores for each road segment by using TOPSIS methodology rather than prioritizing the candidate routes which makes our study to focus on all possible routes. Li et al. (2019), propose a decision support model for risk management of hazardous materials road transportation. They use Fuzzy-AHP to build a hierarchical risk assessment system and determine the importance rating of each risk factor. They focus on direct and indirect risk factors. In our study, by using AHP, in addition to the importance rating of risk factors, we find the importance ratings of cost and consequences factors. Jun and Wei (2010), in their study which is presented in a conference just find the weights of safety, time, and profit by using AHP without including any sub-factors or consequences. Huang (2006) in his study, considers safety, costs, and security. GIS is used to quantify the factors on each link in the network that contributes to each of the evaluation criteria for a possible route. AHP is used to assign weights to the factors; exposure, socio-economic, risks of terrorism, traffic conditions, and emergency response. Each route can then be quantified by a cost function and the suitability of the routes for HAZMAT transportation can be compared. We focus on three main and nine sub-factors which makes our study more comprehensive compared to Huang's study in which only five main factors are considered. Chen et al. (2019) propose a PHFLTS- and TOPSIS-Integrated Multi-Perspective Approach to evaluate and select HazMat Transportation Companies. A case study is applied in China and five candidate companies are sorted by using TOPSIS. TOPSIS is used in a totally different way in our study to find the scores of each road segment.

Geographic Information Systems (GIS) is now widely used in hazmat transportation studies (Ditta et al., 2019) since GIS makes it is possible to attain perfect information about some attributes of road networks (i.e., distances, times, and traffic). For example, Zografos and Androutsopoulos (2008) estimate the total population within a specific selected area by using GIS. Kawprasert and Barkan (2008) use GIS to compute the distance and the type of traffic control system on a HAZMAT transportation network. Rashid et al. (2010) develop a GIS application to build a spatial model for the assessment on the consequences of liquefied petroleum gas release accidents in road transportation. Kim et al. (2011) offer a GIS tool that provides online routing instructions for HAZMAT vehicles given the vehicle's current location and updated information concerning traffic and weather conditions. Samanlioglu (2013) proposes a multi-objective mathematical model for the industrial hazardous waste location-routing problem in which the data is obtained by a combination of GIS software and the regional geographical database. Readers may refer to Holeczek (2019)'s review study for all researches in which GIS is used. Different from the above studies in which GIS is used, we use GIS to find the optimal routes between OD pairs since GIS network analysis tool provides a wide range of network analysis methodologies such as a Dijkstra-based methodology to find shortest paths.

3 Methods

Referring to the past hazmat transportation related researches explained in the introduction and literature review sections, there are three main factors considered in hazmat transportation which are: Risk, Cost, and Consequences.

In almost all hazmat transportation models, as it is summarized by Kang et al. (2014), "$p_{ij}C_{ij}$" is the objective of the model where p_{ij} and C_{ij} are risk and consequences on the road segment (arc) *ij*. A general road network for the hazmat transportation is given in Fig. 1 to explain the objective function of the traditional hazmat transportation models. It is accepted that a hazmat vehicle is going to travel from Origin (node 1) to its Destination (node 7). Let p_{ij} and C_{ij} be the hazmat accident risk and possible consequences on arc *ij*, respectively. x_{ij} is the binary variable and becomes 1 when the arc *ij* is included in the solution.

The objective of the traditional hazmat risk assessment model is to minimize total hazmat accident risks and consequences which is formulated as:

$$\sum \left(p_{ij} C_{ij}\right) x_{ij} \tag{1}$$

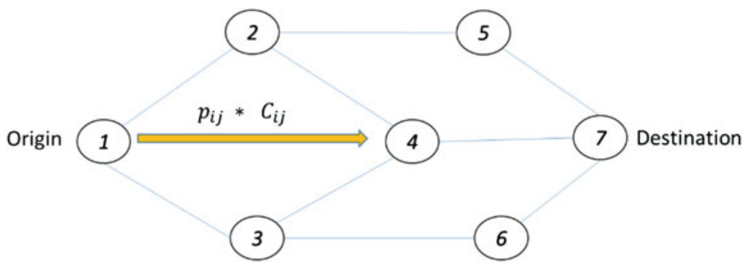

Fig. 1 A general road network for hazmat transportation

Most of the models consider hazmat risk and its consequences as past hazmat accidents and the number of population who will be affected from the accident, respectively. However, we accept that in addition to past hazmat accidents, other risks (i.e., the past accident data of other vehicles and types of the roads) should also be considered in hazmat risk assessments in order to find more realistic solutions. The probability of a hazmat accident is very low (1×10^{-6} on the average on a 1 mile arc in the USA), and there are many arcs on which there are no past hazmat accidents so that the probability becomes zero on those arcs. However, it will not be realistic to accept a zero hazmat risk on arcs since there is always an accident risk if a vehicle is traveling on an arc with a traffic flow. Thus, the probabilities of accidents caused by other vehicle types should also be included in risk assessments on arcs to have a more realistic risk assessment. We also believe that the road types are effective on the occurrence of accidents. For example, the accident probabilities will not be the same in one-way and two-way roads. Eventually, for the hazmat risk assessment main factor we define three sub-factors; past hazmat accidents, past other types of accidents, and road types.

We assign two sub-factors which are driver cost and fuel usage cost for the "Cost" main factor. The last main factor considered in this study is "Consequences" and we assign four sub-factors (referring to past researches), which are population living along the arcs (which is important for fatality and injury estimations), property damage (damage on the hazmat vehicle, other vehicles, and surrounding properties after a hazmat vehicle explosion), environmental damage, and evacuation and clean-up costs (if there is a necessity to evacuate the accident region or clean up the region after a hazmat release). Past researches consider only one factor (usually population) or two factors for consequence analysis. However, our study, to the best of our knowledge is the first study that consider all the factors together. We include all possible main and sub-factors (criteria) in our study which are depicted in Table 1.

The traditional hazmat transportation model (Eq. 1) should be updated with the following formula to include all factors in the objective function:

$$\text{Min} \sum \left[\left(p_{ij}^{T} \, C_{ij}^{T} \right) x_{ij} + \text{Min} \sum \left(\text{Cost}_{ij} \right) x_{ij} \right] \tag{2}$$

where p_{ij}^{T} is the total risk (including R1, R2, and R3 factors), C_{ij}^{T} is all possible consequences (including CN1, CN2, CN3, and CN4), Cost_{ij} is the cost of traveling on arc ij, and x_{ij} is the binary variable and becomes 1 when the arc ij is included in

Table 1 Main and sub-criteria

	Main criteria		
	Risk	Cost	Consequences
Sub-criteria	Past hazmat accidents (R1)	Fuel usage (C1)	Population (CN1)
	Past other accidents (R2)	Driver cost C2)	Property damage (CN2)
	Road type (R3)		Environmental damage (CN3)
			Evacuation and clean-up (CN4)

the solution. We realize that as more factors and objectives are included, the problem becomes more complicated to be solved in a reasonable time. Therefore, in order to reduce the complexity of the problem and find solutions in a reasonable time, we propose a new approach for the hazmat transportation problems which is explained in the following paragraphs.

It is obvious that the aforementioned factors will affect the optimal solution with different weights. So, in the first step of our study, we find the criteria weights by using *AHP methodology* which is developed by Saaty, (Saaty, 1977) for solving decision-making problems. It is one of the most effective multi-criteria decision-making methodology (MDCM) used for finding criteria weights. AHP is described in the following steps:

Decision-Making Problem: In this step, decision points and the factors affecting the decision points are determined.

Creating a Cross-Factor Comparison Matrix: The inter-factor comparison matrix is a dimensional square matrix which is given below. The values of matrix components on the diagonals are 1 since the relevant factor is compared with itself.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}$$

The comparison of the factors is made one to one and mutually according to their importance values. Saaty's factor scale (see Table 2) is used for one-to-one comparison of factors.

Comparisons are made for values that lie above the diagonal of all values of the comparison matrix. For the components under the diagonal, Eq. 3 is used.

$$a_{ji} = \frac{1}{a_{ij}} \tag{3}$$

Table 2 Saaty's 1–9 comparison scale

Level	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favor one activity over another
5	Strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8		Intermediate values

Determining Percentage Importance of Factors: In order to determine the weights of the factors, column vectors forming the comparison matrix are used and column B with nxn components is formed. Equation 4 is used to calculate column B vector values.

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{4}$$

C matrix shown below is created when B column vectors are combined in a matrix format.

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nn} \end{bmatrix}$$

The importance values of the factors relative to each other can be obtained by using Eq. 5.

$$W_i = \frac{\sum_{j=1}^{n} c_{ij}}{n} \tag{5}$$

Measuring Consistency in Factor Benchmarking: Consistency Ratio (CR) and the priority vector provide the possibility to test the consistency of the comparisons. AHP is based on the essence of the CR calculation by comparing the number of factors with a coefficient λ called the Basic Value. After calculating λ, the Consistency Index (CI) can be calculated using the Eq. 6.

$$CI = \frac{\lambda - n}{n - 1} \tag{6}$$

CR is obtained using Eq. 7 and Random Indicator (RI) is shown in Table 3.

$$CR = \frac{CI}{RI} \tag{7}$$

Table 3 Random consistency index

Random consistency index					
N	RI	N	RI	N	RI
1	0	6	1.24	7	1.32
2	0	4	0.9	8	1.41
3	0.58	5	1.12	9	1.45

In addition, a calculated CR value of less than 0.10 indicates that the comparisons made by the decision maker are consistent. Eventually, the weights of the factors (criteria) determined in this study are found by using AHP methodology.

In the second step of this study, the arcs are considered as alternatives (a_{ij}). For all alternatives, we assign the values considering the sub-criteria. In order to assign the risk values; number of the past hazmat accidents and other types of accidents on the arcs (alternatives) are used. Types of the roads that the hazmat vehicles travel are also importantly affect the accident risks and road type values for the arcs are assigned with respect to number of lanes. The related studies, reports, and open-source data are used to assign four consequences (CN1, CN2, CN3, and CN4) values for the arcs. Cost values (C1 and C2) for the arc are assigned considering unit cost for the drivers and fuel cost with respect to distance traveled.

In third step, we use TOPSIS methodology, which is proposed by Hwang and Yoon (1981). It is a very commonly used MCDM methodology for selecting the best alternatives or sorting the alternatives.

In general, the process for the TOPSIS algorithm starts with forming the decision matrix (D) representing the satisfaction value of each criterion with each alternative. The rows show alternatives while columns show criteria in the matrix below:

$$\mathrm{D} = \begin{bmatrix} \mathrm{a}_{11} & a_{12} & \cdots & \mathrm{a}_{1\mathrm{n}} \\ \mathrm{a}_{21} & a_{22} & \cdots & \mathrm{a}_{2\mathrm{n}} \\ \vdots & \vdots & & \vdots \\ \mathrm{a}_{\mathrm{m}1} & \mathrm{a}_{\mathrm{m}2} & \cdots & \mathrm{a}_{\mathrm{nm}} \end{bmatrix}$$

Next, the matrix is normalized with a desired normalizing scheme. In the basic matrix $i = 1,2,\ldots..,\mathrm{m}$ and $j = 1,2,\ldots\ldots.,\mathrm{n}$ values are normalized by using vector normalization below:

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} \mathrm{a}_{ij}^2}}$$

Next, the normalized values (r_{ij}) are multiplied by the criteria weights (we use criteria weights obtained using AHP methodology) to find $\mathrm{V_{ij}}$ values.

Subsequently, the positive-ideal A^+ (associated with the criteria having a positive impact) and negative-ideal A^- (associated with the criteria having a negative impact) values are calculated among $\mathrm{V_{ij}}$ values for each criterion.

The distance of each alternative (S_i^+ and S_i^-) from positive and negative ideal values (A^+ and A^-) is calculated with a distance measure.

Later, the similarity to the worst condition ($C_i^{+)}$ is calculated:

$$C_i^+ = \frac{S_i^-}{S_i^+ + S_i^-}$$

Finally, the alternatives are ranked based on their relative closeness to the ideal solution.

Eventually, after applying TOPSIS, we find unique values for each alternative a_{ij} in which all sub-criteria values are considered. So, we propose Eq. 8 to be used instead of Eq. 2.

$$\sum \left(a_{ij}\right) x_{ij} \tag{8}$$

where a_{ij} is the value (that is obtained from AHP-TOPSIS methodologies) for arc *ij* which include all the aforementioned factors.

In the last step, rather than writing a linear model which also includes Eq. 8 in the objective function, we use ArcGIS to find the optimal routes between the OD pairs in which those unique values of alternatives are minimized. ArcGIS usage is a very practical way of finding optimal routes. The changes in the related data may require writing new linear models in the studies in which linear models are proposed. However, those changes can easily be adopted for ArcGIS which makes it a more practical tool for finding optimal routes.

Hazmat transportation problems are generally large-scale problems and excessive computational requirements are needed so that many researchers propose heuristic solutions. The bi-objective (risk and cost) hazmat problems are usually solved by the proposed heuristic models. We propose a new approach to overcome the large-scale hazmat transportation problems. Another important contribution of the study is that all factors (including risk and cost) of hazmat transportation are considered together in this study so as to find optimal solutions and hence both the concerns of carries (main concern is cost) and the legal authorities (main concern is risk) are satisfied. In addition, our methodology gives the opportunity to ban some of the arcs on the road network and find optimal solutions without including those banned arcs.

4 Case Study Findings

In this section, we present a *Case Study* in Istanbul, Turkey to find the optimal routes for hazmat vehicles in order to show the efficiency of the proposed methodology. In the first step of our analysis, the experts who work on hazmat transportation and recently published articles in Web of Science indexed journals are asked to fill out a questionnaire that includes comparisons for main and sub-criteria. Eight experts from the USA, Canada, Brazil, Italy, China, Iran, and Turkey filled out our questionnaire in helping this study. The experts are chosen from the countries in which hazmat transportation has an important share. Note that those counties are chosen from the most crowded continents (Asia, North and South America, Europe), which are located in different regions of the world. Those experts are aimed to bring a multinational and cross-continental perspective while assigning

Table 4 Main and sub-criteria weights

Main criteria	Weight	Sub-criteria	Weight-1	Weight-2
Risk	0.249	Past hazmat accidents	0.3415	0.0852
		Past other type vehicle accidents	0.1780	0.0444
		Road type	0.4805	0.1198
Cost	0.109	Fuel usage	0.5000	0.0543
		Driver cost	0.5000	0.0543
Consequences	0.642	Population	0.6025	0.3868
		Property damage	0.0743	0.0477
		Environmental damage	0.2334	0.1499
		Evacuation and clean-up cost	0.0898	0.0576
Total	1.000		Total	1.000

importance weights for main and sub-criteria. Their replies are analyzed using AHP methodology steps explained in the third section in order to find the importance weights of the factors. The importance weights for main and sub-criteria are given in Table 4.

We find that the most important main criteria for hazmat transportation is "Consequences" with a score 0.642. "Risk" and "Cost" have 0.249 and 0.109 criteria weighs. Weight-1 column shows the sub-criteria weights for each main criterion. For example, the sub-criteria weights for "Risk" main criteria are found as 0.3415, 0.1780, and 0.4805 for past hazmat accidents, past other type vehicle accidents, and road type sub-criteria, respectively. Main criteria weights (scores in Weight column) and sub-criteria weights (scores in Weight-1 column) are multiplied to find the sub-criteria scores in general (Scores in Weight 2 column). For example, among 9 sub-criteria, "Population" has the greatest weight score which is 0.3868. Second most important sub criteria is found as "environmental damage" with a score 0.1499. All CR values in our AHP analysis are below 0.06, which is less than the edge value 0.1 that makes our analysis consistent.

In the second step, we obtain and adopt the case study data for TOPSIS analysis which will be focused in the third step. We select Istanbul-Bahçelievler for the case study. Istanbul is the most crowded city in Turkey with a population of over 15 million. Thousands of tankers carry fuels to meet the demand in fuel stations. Many fuel stations unfortunately are located in the crowded parts of the urban areas in Istanbul. Hazmat transportation is very important in terms of both cost and risk. An explosion of a hazmat vehicle may cause hundreds of casualties, thousands on injuries, and million dollars of cost. Istanbul has a great road network and we prefer to focus on Bahçelievler which is a town of Istanbul for our case analysis. Bahçelievler road network includes 8508 arcs. Those arcs are considered to be alternatives in TOPSIS analysis. We need the scores of those arcs with respect to nine sub-criteria in order to apply TOPSIS analysis. The explanation of how the related data for nine sub-criteria considered in this study is adopted for our case study is given in Table 5.

Table 5 DATA collection and adaptation for the case study

Factor (Criteria)	DATA collection and adaptation
Past hazmat accident	The real data for 2018 are obtained from the Istanbul police headquarters. There is only yearly accidents data for towns of Istanbul. We distributed Bahçelievler's hazmat accidents for the year 2018 to its districts evenly with respect to a total distance of road networks of the districts.
Past other types of accidents	The accidents data for all districts of Bahçelievler for 2018 are obtained from the Istanbul police headquarters. The district accidents data are evenly distributed to the arcs with respect to the arc lengths.
Road type	We use Istanbul road network data in terms of "shape file" format to be used in ArcGIS tool. Road types are available in this file.
Driver cost	The average driver cost for Istanbul is accepted to be ₺ 4000 (₺: Turkish Lira) per month. The drivers work 40 hour a week and 160 hours per month. The hourly rate is accepted to be ₺25. We first assigned average hazmat vehicle speeds on the arcs with respect to road types. Next, we find the time to travel on each arc. The hourly driver cost is adopted for the arcs according to the travel times on those arcs.
Fuel cost	Fuel costs for the arcs are assigned with respect to arc lengths. So, the arcs with greater lengths are assigned greater fuel costs.
Population	The population of the districts of Bahçelievler for the year 2019 is available on the official website of Bahçelievler government given below: http://www.bahcelievler.gov.tr/bahcelievler-in-nufus-durumu The district populations are evenly distributed to the arcs with respect to the arc lengths. So, the longer arcs are assigned greater population values.
Property damage	The property damage values for the arcs are assigned with respect to road widths. We consider that the traffic density will be higher in the arcs with wider widths causing greater property damage due to greater presence of vehicles around hazmat accident point.
Environmental damage	We assign "1" for the arcs closer to the parks, green areas are and "0" for the arcs away from the parks and green areas. So, we force the ArcGIS tool to select the arcs with "0" values.
Evacuation and clean-up	We consider that evacuation costs will be higher for crowded areas. We assign greater values for the arcs closer to schools, hospitals, and libraries.

In the third step, we apply TOPSIS analysis explained in Sect. 3. We use the sub-criteria weights found in first step while applying TOPSIS. We combine nine sub-criteria scores for each arc to one unique score by applying TOPSIS. Eventually, we find scores for 8508 arcs. Those scores are between 0 and 1. Since the objectives in all criteria are minimization, the arcs with the scores closest to zero are considered to be best options for finding optimal routes.

In the last step of this study, we use ArcGIS network analysis tool which minimizes those scores while finding optimal routes between OD pairs. TOSIS scores of all arcs are imported and ArcGIS network analysis road networks are constructed to find optimal routes. We first find optimal routes for four OD pairs with respect to TOPSIS score, which includes and represents all nine criteria scores. Next, we also find optimal routes with respect to the objectives; minimizing past hazmat accidents, past all vehicle accidents, travel cost, and population encounter

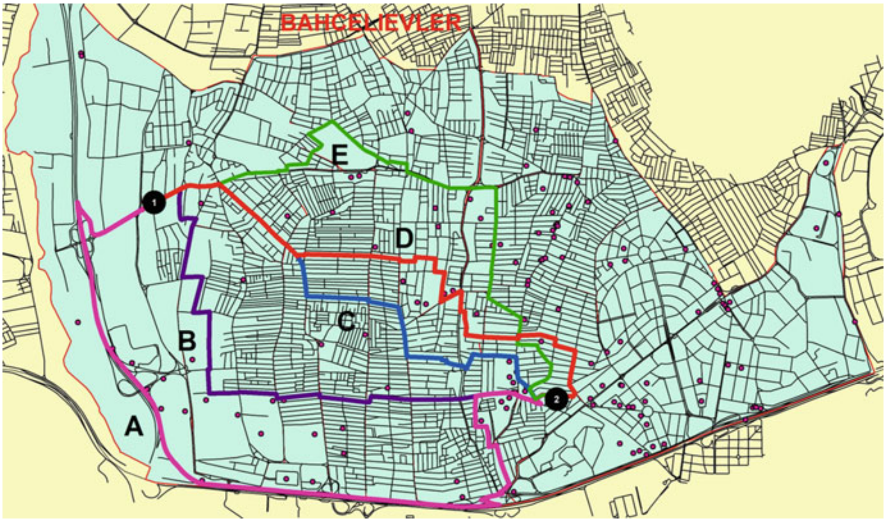

Fig. 2 Routes found for first OD pair

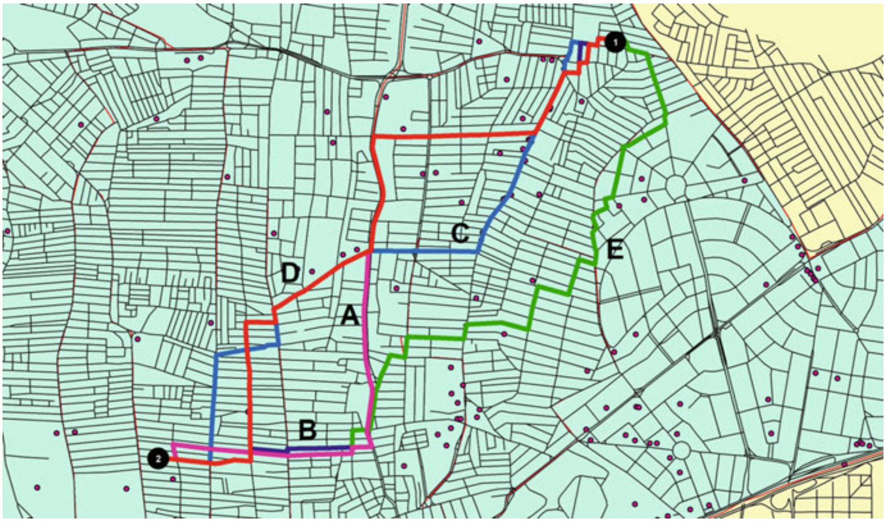

Fig. 3 Routes found for second OD pair

the hazmat risk in order to apply a comparison analysis. Figures 2, 3, 4, and 5 show the routes found from origin 1 to destination 2. We select different origins and destinations for each trial. The optimal routes found for 5 different objectives are represented with different colors. The routes A, B, C, D, and E given in red, pink, dark blue, blue, and green colors are the optimal routes found for the objectives which minimize TOSIS score, past total accidents (all vehicle accidents),

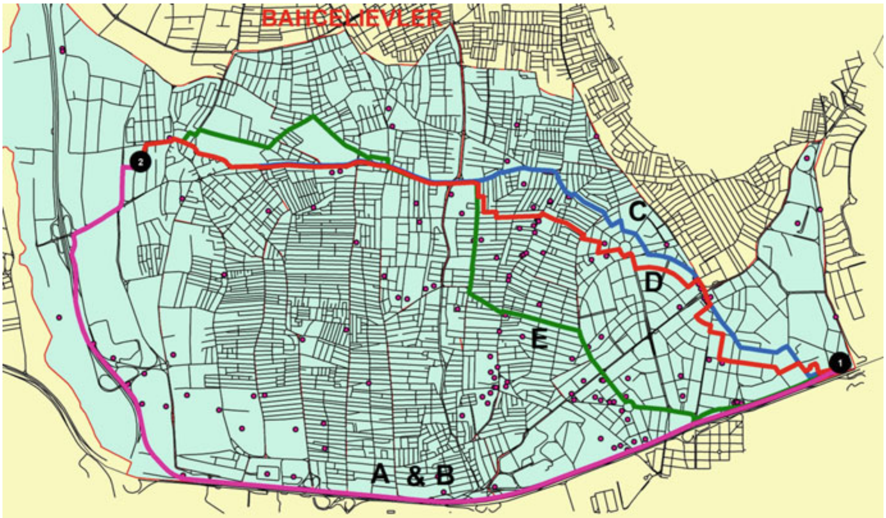

Fig. 4 Routes found for third OD pair

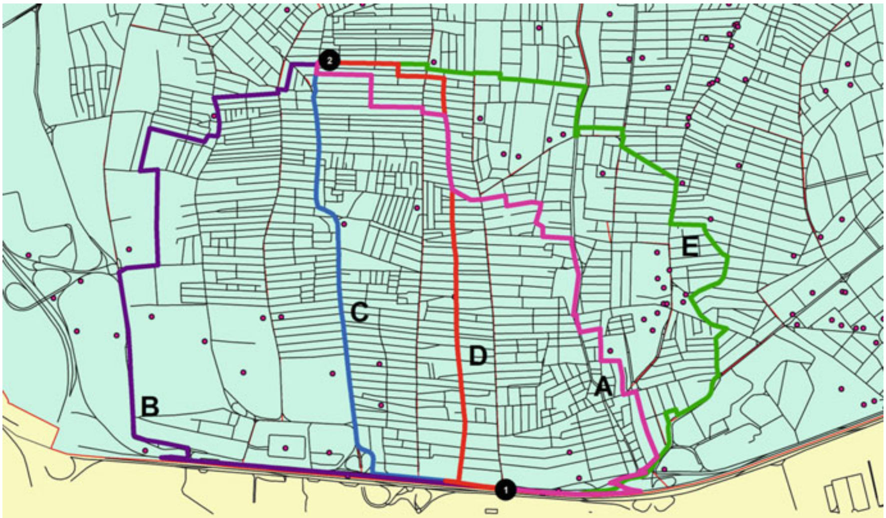

Fig. 5 Routes found for fourth OD pair

past hazmat vehicle accidents, cost, and population respectively. Bahçelievler town region is given in blue shaded area in the figures, in which black lines show the road network. Color codes of objectives and scores of routes are given in Table 6.

We find different optimal routes considering 5 different objectives for the first, second, and fourth OD pairs. However, the routes found for the objectives which minimize total accidents and hazmat accidents are same in third OD pair (the route with pink color in Fig. 4).

Table 6 shows route names and color codes, 5 different objectives, and the scores found for those objectives for 4 OD pairs.

For each OD pair, there are 5 routes found for 5 objectives and their corresponding scores are depicted in Table 6. When we focus on the routes found for the first OD pair; first row shows the scores of route A with pink color considering 5 criteria which are given in "Route Scores Considering 5 Criteria" columns. The objective of first row is minimizing past total accidents and the corresponding past total accident score for route A is found as 582.63. The others scores given in the other columns of route A are the scores of route A considering other 4 criteria and distance. The scores of 4 other routes (B, C, D, and E) are given in the following rows of Table 6 for first OD pair. When the scores for "Total Ac." column for first OD pair is compared, we see that best score belongs to route A (marked with *) since the objective is minimizing past total accidents. The *-marked scores in the columns of Table 6 show the best routes for the corresponding objectives.

In this study, we propose to use TOPSIS scores for finding the optimal routes which take into account all criteria. We compare scores of red routes (in which TOPSIS scores are minimized) with the scores of other routes so as to show if our proposal is realistic. For example, when we focus on "Population" column, of course, the best routes are green color routes in which the only objective is to minimize hazmat risk on the population. We realize that the second best scores for 4 OD pairs considering population belong to red routes. In addition, the red routes again have the second best scores for "Cost" and "Distance." When the accidents are considered (total and only hazmat accidents), the red routes give the third best scores after the total accidents and hazmat accidents routes. Eventually, if we focus only on one objective while finding the optimal route for a hazmat vehicle, we should prefer the routes found for the corresponding objective. However, if we aim to find optimal routes by considering all criteria, our proposed methodology which uses the scores obtained using AHP-TOPSIS methodologies gives the best solutions for finding optimal routes.

We conduct a sensitivity analysis and examine the effects of the changes in the weights of the main criteria (risk, cost, and consequences) focused on this study. Table 7 depicts 5 different weight compositions of the main criteria. The weights given in TOPSIS 1 column are the originally found weights (recall Table 4). We assign the same weights (0.333 for each criterion) for the main criteria in TOPSIS 2 column.

We find the optimal routes (Fig. 6) which minimize the TOPSIS scores with respect to 5 different weight compositions.

We realize that optimal routes may change when the main criteria weights are changed since we found 5 different optimal routes for 5 different weight compositions. Table 8 shows route names and color codes, 5 different objectives in which TOPSIS scores (T1, T2, T3, T4, and T5) are minimized with respect to 5 different weight compositions and the scores found for those objectives (accidents,

Table 6 Case study scores for 4 trials

				Route scores considering 5 criteria					
OD pair	Route name	Route color	Route objective (Min. of)	Total Ac.	Hazmat Ac.	Cost (TRY)	TOPSIS	Population proportion	Distance (meters)
1	A	Pink	Total Ac.	582.63*	80.04	20.54	4.71	494.84	7653.77
	B	D. Blue	Hazmat Ac.	703.63	72.31*	13.98	3.50	351.19	5158.67
	C	Blue	Cost	1138.63	138.87	11.58*	3.18	265.92	4321.44
	D	Red	TOPSIS	1265.63	132.04	13.27	2.64*	248.07	4918.36
	E	Green	Population	2490.63	235.87	14.89	4.18	211.33*	5574.11
2	A	Pink	Total Ac.	440.63*	62.13	10.87	1.84	174.23	4026.68
	B	D. Blue	Hazmat Ac.	488.63	61.75*	10.79	1.84	173.85	3999.27
	C	Blue	Cost	1088.63	115.79	9.42*	2.40	172.07	3539.14
	D	Red	TOPSIS	665.63	67.49	10.27	1.76*	162.45	3801.38
	E	Green	Population	1821.78	146.86	11.58	2.13	131.49*	4260.89
3	A	Pink	Total Ac.	1053.50*	67.62	22.27	3.88	452.15	8342.36
	B	D. Blue	Hazmat Ac.	1053.50	67.62*	22.27	3.88	452.15	8342.36
	C	Blue	Cost	3241.57	186.75	17.36*	3.83	286.22	6538.47
	D	Red	TOPSIS	2707.57	161.88	19.14	3.32*	280.66	7150.97
	E	Green	Population	3709.57	248.36	19.95	4.47	245.45*	7405.78
4	A	Pink	Total Ac.	442.30*	64.22	11.91	2.24	252.66	4408.84
	B	D. Blue	Hazmat Ac.	640.73	40.35*	13.05	3.25	380.86	4892.25
	C	Blue	Cost	1076.73	87.83	7.29*	2.01	205.45	2678.07
	D	Red	TOPSIS	693.70	61.44	7.65	1.61*	180.62	2808.46
	E	Green	Population	2391.27	229.02	12.90	3.21	141.50*	4791.12

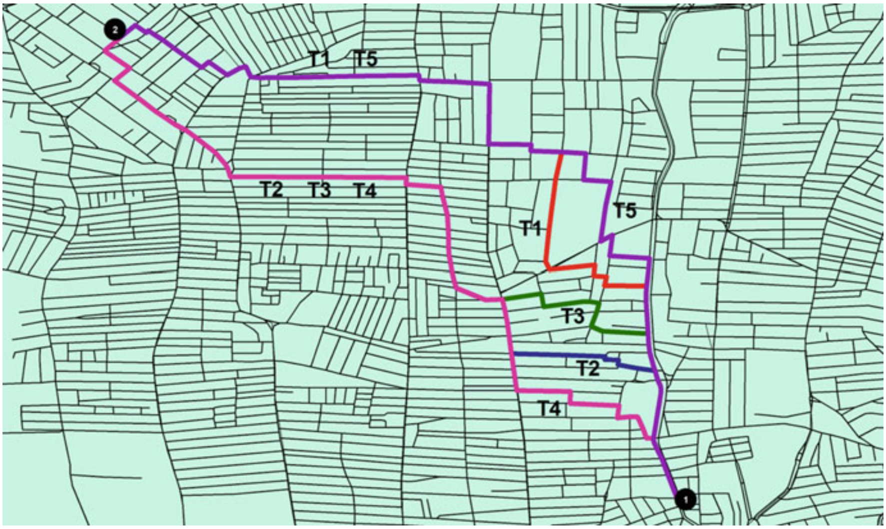

Fig. 6 Routes found for different criteria weights

hazmat accidents, cost, population exposure, and distance traveled). Optimal scores for each column are marked with * and ♦.

Green route (T3) gives the best scores if "Total Accidents" and "Hazmat Accidents" columns are considered since the criterion weight assigned for risk is the highest (0.6) in this route. Pink route (T4) gives the best scores if "cost" and "distance" traveled are considered since we assign 0.6 for cost criterion in this route so as to mostly minimize the cost of travel. The criterion score that we assign for "Consequences" is 0.6 in Purple route (T5). Hence, we obtain best score of "Population" column in route T5 since the main focus is on consequences in this route. Eventually, the sensitivity analysis proves that the optimal routes may change when the weights of the criteria are changed. In this study, we first find the criteria weights with respect to the opinions of experts who study on hazmat transportation and next find optimal routes by taking into account those weights. However, the decision makers may put more emphasis on some criteria which causes changes in the criteria weights and optimal routes can be found accordingly using our methodology.

Table 7 Different weight compositions of the main criteria

AHP Weight	TOPSIS 1 (T1)	TOPSIS 2 (T2)	TOPSIS 3 (T3)	TOPSIS 4 (T4)	TOPSIS 5 (T5)
Risk	0.249	0.333	0.600	0.200	0.200
Cost	0.109	0.333	0.200	0.600	0.200
Consequences	0.642	0.333	0.200	0.200	0.600

Table 8 Scores of the routes found in Fig. 6 for different objectives

Route name	Route color	Obj. (Min.of)	T1	T2	T3	T4	T5	Total Ac.	Haz. Ac.	Cost TRY	Pop.	Dist. (m)
T1	Red	T1	1.806*	1.969	2.222	1.987	1.808	705.3	73.8	9.185	192.7	3403
T2	D.Blue	T2	1.840	1.928*	2.179	1.894	1.823	513.3	65.2	8.433	207.6	3131
T3	Green	T3	1.845	1.943	2.176*	1.927	1.834	485.3 ◆	63.4◆	8.651	210.1	3205
T4	Pink	T4	1.864	1.947	2.234	1.893*	1.840	574.3	69.9	8.389◆	208.2	3115◆
T5	Purple	T5	1.808	1.972	2.245	1.985	1.807*	788.3	77.0	9.176	191.6◆	3404

5 Discussion

In this study, we propose a practical methodology to find optimal routes for hazmat vehicles considering three main and nine sub-criteria. The main focuses in the studies which are introduced in the literature survey are hazmat accident risk and the consequences. Most of the studies consider population exposure as consequence and propose solutions in which the hazmat risk on the population living along arcs is decreased. Some studies also consider risk and cost together by proposing bi-level models to find optimal routes. Different from the other studies, we include all those risks and consequences and additionally the other vehicle's accident risk in our proposed model which we believe shows the strength of our study. The results of the case study are important to explain the contribution of our study. The score change proportions between optimal routes for 4 OD pairs are given in Table 9. Most important factors in hazmat transportation are considered as hazmat accident risk, cost, and population exposure referring to the past studies. Hence, we compare our proposed study results with the results in which only hazmat accident risk or cost or population exposure are considered. For example, if the results for OD pair 4 are compared we see that when the optimal route (red route) found using our proposed methodology (TOPSIS row in OD Pair 4 in Table 9) is used hazmat accident risk will be increased by 1.52 times rather than using the optimal route found in which hazmat accident risk is minimized. The red route will also increase the cost and population exposure 1.05 and 1.28 times, respectively. However, if the route which only minimizes population exposure (Population row in OD Pair 4) is used, hazmat accident risk and cost will be increased 5.68 and 1.67 times. The increases are higher

Table 9 Comparison of optimal routes for 4 OD pairs

OD Pair	Route	Hazmat Ac.	Cost (TRY)	Population
1	Hazmat Ac.	1.00	1.21	1.66
	Cost	1.92	1.00	1.26
	TOPSIS	1.83	1.15	1.17
	Population	3.26	1.29	1.00
2	Hazmat Ac.	1.00	1.15	1.32
	Cost	1.88	1.00	1.31
	TOPSIS	1.09	1.09	1.24
	Population	2.38	1.23	1.00
3	Hazmat Ac.	1.00	1.28	1.84
	Cost	2.76	1.00	1.17
	TOPSIS	2.39	1.10	1.14
	Population	3.67	1.15	1.00
4	Hazmat Ac.	1.00	1.79	2.69
	Cost	2.18	1.00	1.45
	TOPSIS	1.52	1.05	1.28
	Population	5.68	1.77	1.00

than TOPSIS route if the routes which minimize hazmat accident risk or cost are used (see the scores in OD Pair 4). So, using our proposed methodology will give better solutions than focusing only on the important factors separately as in the previous studies.

Our methodology also considers other factors such as other types of vehicle's accident risk, property damage, environmental damage, evacuation, and clean-up cost while finding optimal routes for hazmat vehicles. All nine sub-criteria focused in this study affect the optimal route with different weights and those weights are found using AHP methodology. We consult the researchers who focus hazmat transportation in their studies rather than consulting legal authorities (who prefer to decrease hazmat risk on the population) or carriers (who prefer to decrease the cost of transportation). To the authors' best of knowledge, this is the first study in which weights of three main and nine sub-factors are found.

6 Conclusions

In this study, we determine three main and nine sub-factors together for hazmat transportation referring to previous studies. Next, the researchers who publish hazmat transportation related studies are asked to compare main and sub-factors and their comparison scores are used to find importance weights of main and sub-factors using AHP methodology. We find that the most important main criteria for hazmat transportation are "Consequences" with a score 0.642. "Risk" and "Cost" have 0.249 and 0.109 criteria weighs. Regarding nine sub-criteria, "Population" has the greatest weight score which is 0.3868 and second most important sub-criteria are found as "environmental damage" with a score 0.1499. To the best of our knowledge, our study is the first study in which all criteria weights are found.

Next, the arcs on a road network are considered as alternatives and one score for each arc is found by combining the data which belong to nine factors using TOPSIS methodology and criteria weights found in the first step. This is the first study that TOPSIS is used in this way to combine the data for nine factors into one score for arcs on the road network.

Finally, optimal routes between OD pairs are found using ArcGIS network analysis tool in which total route score is minimized. We compare the optimal routes found using our methodology and the methodology used in previous studies. We also conduct a sensitivity analysis and examine the effects of the changes in the priorities of the criteria weights on the results. The results encourage us to propose our methodology in which all hazmat transportation related factors are included while finding optimal routes for hazmat vehicles. Our study proposes a more practical methodology for finding optimal routes comparing with studies in the literature which propose very complicated mathematical models and solution ways. Another important advantage of our methodology is that when some of the values related to constraints or parameters are changed, this can easily be adopted in our model to find optimal routes between any OD pairs on the road network in a very short time. In addition, our study which uses ArcGIS to find optimal routes is available to ban the arcs with higher scores (which include the scores of nine factors) while finding optimal routes.

For future studies, our methodology can be adopted to find optimal routes for other vehicles carrying different kinds of cargoes since there are also other related criteria that affect the other transportation types and our methodology can be used to find first the criteria weights and next the optimal routes between OD pairs.

Our study is the first study in which criteria weights are assigned for hazmat transportation. The researchers can use main and sub-criteria weights found in this study in their researches in which other types of mathematical models and solutions are used.

We aim to include a multinational perspective while assigning criteria weights. Our questionnaire can be applied to the local experts in further studies if the main focus is on hazmat transportation inside the country.

We use AHP methodology to find the criteria weights. Other MDCM methodologies can be used in future studies to find the criteria weights and the results obtained from those methodologies can be compared.

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