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Invited Review

Hazardous material transportation problems: A comprehensive overview of models and solution approaches

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ABSTRACT

This paper provides a comprehensive review in the domain of hazardous material transportation from an Operational Research point of view. The paper's focus lies on hazmat routing, routing-scheduling, and network design problems. The objective of this review paper is twofold: (1) reviewing the models' assumptions, objectives and constraints, decisions, input parameters, basic modeling/solution techniques, and case studies, and (2) highlighting the underlying features and challenges in designing the models with different transportation modes. Besides, the most significant research gaps in the literature are identified through a systematic in-depth review at a micro-level. Finally, a set of promising future research directions is proposed upon from the authorities could draw better decisions. As a key finding after performing this review, we believe that a considerable number of promising future research directions consist in hybridizing different problems, i.e., amount to borrowing some key properties from a problem and integrating them into another problem. This has led to valuable research studies in the literature of hazmat transportation problems.

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1. Introduction

Hazardous material (hazmat) is defined as a type of material with the potential to harm people, the environment, and properties. They consist of explosive, combustible, oxidizing, toxic, radioactive, infected, or acidic substances and hazardous wastes. Different processes in manufacturing/service industries like chemical plants, nuclear plants, hospitals, and petroleum refineries typically generate hazmat. Hazmat transportation from a primary origin (e.g., an oil platform) to an industry (e.g., a chemical plant) and then to storage or utility locations is a serious challenge. The hazmat transportation may include intra- or inter-cities and countries' transportation networks using different modes. Possible threatening incidents due to the displacement of hazmat may occur during loading, unloading, or shipping processes. Although the frequency of hazmat incidents is not significant compared to other accidents in transportation networks, the consequences are disastrous; thus, they are categorized as low-probability-high-consequence events. It can be inferred from Tables 1 and 2 that hazmat transportation incidents that occurred in the U.S. are indeed low-probability and high-consequence transportation accidents.

The increased risk associated with hazmat transportation incidents has raised the awareness of different sectors including industries, government, and academia. In the latter sector, numerous researches are done to evaluate and reduce the risks in hazmat transportation, wherein the risk is an indicator of the probability and severity of loss to an exposed receptor due to potential unwanted events regarding a hazmat (Alp, 1995). In this regard, the problems that are commonly addressed include (1) Hazmat Risk Assessment/Analysis (HRA), (2) Hazmat Routing (HR), (3) Hazmat Routing-Scheduling (HRS), (4) Hazmat Facility Location (HFL), (5) Hazmat Location-Routing (HLR), and (6) Hazmat Transportation Network Design (HTND) (Erkut, Tjandra & Verter, 2007). Operational Research (OR) models and more precisely mathematical optimization techniques have gained expressive attention in academia to model and solve hazmat transportation problems with

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Table 1
Number of transportation and hazmat transportation accidents in the U.S. from 2015 to 2017.

Transportation mode	No. of accidents								
	Total			Hazmat			Hazmat/Total (%)		
	2015	2016	2017	2015	2016	2017	2015	2016	2017
Road	6296,000	6821,000	6452,000	15,124	16,527	15,742	0.24%	0.24%	0.24%
Rail	10,273	9967	10,332	581	545	571	5.66%	5.47%	5.53%
Water	7488	6863	6545	24	11	9	0.32%	0.16%	0.14%

Table 2
High consequence hazmat incidents in the U.S. (U.S. Department of Transportation, 2019).

Transportation mode	Year	City/location	Type	Total No. of fatalities	Total No. of injuries	Total damages ($)
Air	1996	Miami	Oxidizer	110	0	Not reported
Water	1993	Pass Christian (Gulf Intracoastal Waterway)	Compressed gas	0	0	5400,000
Road	1991	Bronx	Flammable	5	0	1052,000
Rail	2005	Graniteville	Poisonous gas	9	631	8018,600

respect to particular objectives (e.g., minimizing risk, minimizing cost, etc.) (Erkut et al., 2007). Till now, a considerable number of studies have contributed to the application of OR models to hazmat transportation.

To the best of our knowledge, Erkut et al. (2007) is the only paper that offers a truly comprehensive review of hazmat transportation from an OR point of view. As an up-to-date comprehensive analysis, this paper aims at providing an in-depth review of papers addressing hazmat transportation with a focus on HR, HRS, and HTND problems from an OR viewpoint. For each class of these problems, this paper details the historical development and points out recent trends. Moreover, research gaps and new potential challenges are identified. Such an in-depth review should facilitate access to the field of hazmat transportation for new researchers.

1.1. Search methodology and scope of the study

As explained earlier, this paper reviews the studies addressing HR, HRS, and HTND problems. The main reason is that these problems not only involve the main decisions in hazmat transportation (i.e., location, routing, scheduling, network design, etc.), but also share mostly the same properties from an OR viewpoint. Therefore, this paper does not review hazmat problems that involve location decisions (i.e., HFL and HLR). Moreover, HRA problems are excluded from the research scope of this paper since this problem has not been significantly studied in recent years and has been reviewed comprehensively (List et al., 1991; Erkut et al., 2007). We also classify papers according to the corresponding mode of transportation including road, railway, intermodal or multimodal, airway, and maritime.

Initially, the process of identifying the relevant papers began by looking for the combination of ("*routing*" OR “scheduling” OR "*routing-scheduling*" OR "*transportation*" OR "*network design*") AND ("*hazmat*" OR "*hazardous*") in the title, abstract, and keywords of the documents from 1980 to July 2021. The search combination was applied in three well-known search engines: Google Scholar, Web of Science, and SCOPUS. The number of publications found based on the selected keywords within the selected time frame was overwhelming. We then filtered the documents to limit the scope of this paper to articles published in top-ranked and leading journals. The procedure of filtration, as well as the list of remained journals, have been provided in Appendix A. Full-text screening was finally done on the remaining documents to remove irrelevant papers. During the full-text screening, papers' references were also reviewed to assure the relevance of selected papers. Finally, a set of 90 papers were retained, wherein 52, 15, and 23 papers correspond to HR, HRS, and HTND problems, respectively.

Fig. 1 illustrates the annual trend with a 5-year moving average of the total and the detailed number of published papers in the literature from 1980 to July 2021 for HR, HRS, and HTND problems. As can be seen, the number of studies on HR, HRS, and HTND problems increases, especially from 2005 to date. Until 2004, a total of 24 papers had been published among which 21 articles dealt with HR problems. From 2005 to 2015, a total number of 36 papers were published, among which HRS and HTND problems have gained equal popularity, with 9 and 10 articles, respectively. From 2016 to 2021, the number of published articles addressing HTND problems (12 articles) significantly exceeds the number of studies on HRS problems (4 articles) and nearly equals the number of papers on HR problems (14 articles). This trend demonstrates the higher importance of studying HTND problems in these years in comparison to HR and HRS problems.

1.2. Contributions of this paper

Table 3 provides a comparison between this paper and the existing relevant review papers in the literature.

The review papers provided by Abkowitz, List and Radwan (1989), List et al. (1991), and Kleindorfer and Kunreuther (1994), are quite outdated reviews without an OR viewpoint and they study neither HTND problems nor the role of transportation modes. Erkut et al. (2007) offer the most comprehensive review with an OR viewpoint on HRA, HR, HRS, HLR, and HTND problems from 1980 to 2007. This paper focuses more on the HRA problem while other problems were left undetailed. Recently, Ditta, Figueroa, Galindo and Yie-Pinedo (2018) and Holeczek (2019) published two review articles on hazmat transportation problems, but from other aspects than an OR viewpoint. Ditta et al. (2018) have classified the articles studying HRA, HR, HLR, and HTND problems based on their contribution to data analysis, model, and theory. Moreover, the authors have not detailed the features of each article and they have only examined the assumptions underlying each problem and labeled them as being realistic, limited, or unrealistic. Holeczek (2019) has reviewed the literature on HR, HRS, HLR, and HTND problems at a macroscopic level with a focus on the road transportation mode. In addition to these six review articles, Hamdi, Labadie and Yalaoui (2014) and Erol and Yilmaz (2016) are other relevant review papers; however, these are short papers and have not adopted an OR viewpoint to examine the literature.

Differing from other review papers and as the first in its kind, this paper provides a comprehensive but microscopic review on three important and well-studied problems in hazmat transportation (i.e., HR, HRS, and HTND) from an OR viewpoint. Moreover,

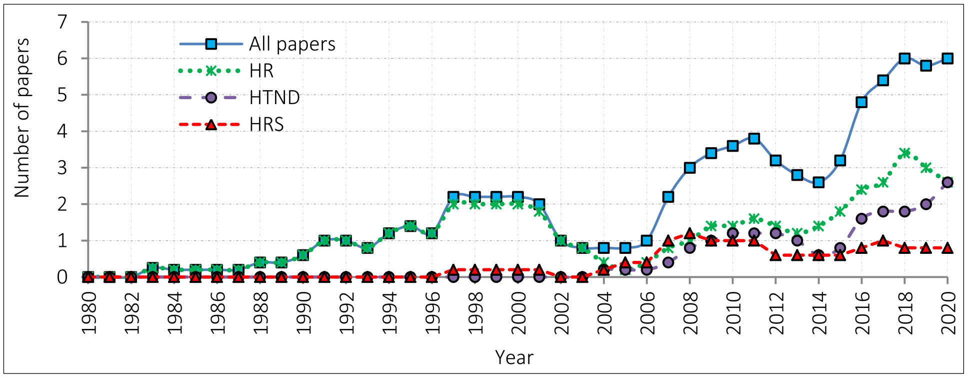

Fig. 1. Trend (5-year moving average) of reviewed articles in this paper. There is only a single paper published during the first three months of 2021; hence, it is counted within the papers of 2020.

Table 3
Major facets of the existing review papers in the literature comparing to this paper.

Reference	OR view	Review type	Year		Scope						
			From	To	Problem type						Transportation mode classification
					HRA	HR	HRS	HFL	HLR	HTND	
Abkowitz et al. (1989)	–	Ma	1973	1989	+	+	±	–	–	–	–
List et al. (1991)	–	Ma	1981	1991	+	+	+	+	+	–	–
Kleindorfer and Kunreuther (1994)	±	Ma	1978	1994	–	–	–	+	±	–	–
Erkut et al. (2007)	+	Ma	1982	2007	+	+	±	–	+	+	–
Ditta et al. (2018)	–	Ma	2008	2016		±	±	–	±	±	–
Holeczek (2019)	±	Ma	1973	2017	–	+	+	–	+	+	–
This paper	+	Mi	1973	2021	–	+	+	–	–	+	+

+ = satisfied, - = not satisfied, ± = partially satisfied, Ma = macro level, Mi = micro level

this paper attempts to provide a detailed discussion on the role of transportation modes in these problems.

1.3. Organization of the paper

The main goal of this section is to explain how the rest of this paper proceeds and to serve as a guideline for interested readers. To provide a comprehensive but detailed OR viewpoint on the problems under scrutiny, the main properties of each article will be identified. These properties include assumptions, objectives, constraints, decisions, input parameters, type of modeling, solution techniques, and case studies. Throughout this paper, we attempt to detail these properties and classify the papers, in each problem category, based on the detailed characteristics of each property. This requires to first identify the detail of each property. With regards to that, Section 2 provides the main properties as well as the details of each property. In addition, Section 2 offers useful preliminary definitions that are referred to throughout the manuscript. Next, Sections 3–5 are dedicated to HR, HRS, and HTND problems, respectively, wherein the relevant papers are classified/analyzed and literature gaps are discussed. The reviewed papers for each problem are classified based on each property in a separate sub-section. Each sub-section contains a classification table, technical comments/notes on the articles of the table (if applicable), a statistic on the papers in each table (if possible), and a global discussion on the trends and valuable information that can be inferred from the classification tables. The technical notes contain a set of information that cannot be included in the tables but that we believe to be valuable including particular and new concepts that an article may have incorporated in the modeling of the corresponding problem. Furthermore, a basic mathematical model for each of the problems is provided in Appendix B. After classifying/analyzing the problems individually, Section 6 provides a discussion on similarities and dissimilarities in the properties of HR, HRS, and HTND problems. Due to the important role of transportation modes when developing an OR model for hazmat transportation, Section 7 is devoted to highlighting and discussing this importance in different problems. Finally, the review is concluded in Section 8 and general future research directions are elaborated.

2. Preliminaries

This section first proposes a detailed classification of the properties of the reviewed papers from an OR viewpoint. Second, it provides explanations on a set of quantitative measures utilized when modeling a hazmat transportation problem.

2.1. Classification of properties

This section aims at identifying the main properties of the studies on hazmat transportation problems from an OR viewpoint (i.e., assumptions, objectives, constraints, decisions, input parameters, type of modeling, solution techniques, and case studies). Each of these properties is then broken down into more details.

Table 4 lists the main as well as the detailed properties of the reviewed articles. Column "Property" introduces the main properties in a study from an OR viewpoint. The next two columns explain how each main property can be broken down into more detailed properties that have been incorporated in the reviewed articles. It should be mentioned that Table 4 covers all the properties incorporated in the reviewed articles; therefore, each article may possess only a few of these. Taking "Assumptions" as an example of the main property, we identified that the reviewed papers have assumed various types of Origin-Destination (OD) pairs to transport the hazmat such as single OD pair, multiple OD pairs, one depot, and multiple destination pairs, etc. Other properties in Table 4 can be interpreted similarly.

Table 4
General properties and details of HR, HRS, and HTND problems.

Property	Type	Details
Assumptions	OD pairs	1) Single OD pair, 2) Multiple OD pairs, 3) Single depot and multiple customers, and 4) Multiple depots and multiple customers
	Planning horizon	1) Single time period and 2) Multiple time periods
	Players (involving sectors)	1) Carrier, 2) Government, and 3) Others players such as freight forwarder, emergency responder, environmentalist, or local authority
	Parameter type	1) Deterministic (DE), 2) Dynamic (DY), 3) Stochastic (ST), 4) Probabilistic (PR), 5) Fuzzy, 6) Possibilistic (PO), and 6) Real time (RT)
	Vehicle type	1) Homogenous and 2) Heterogeneous
	Hazmat class	1) Single commodity and 2) Multiple commodities
Constraints	Constraints to assure equity	1) Risk on each link, 2) Risk on each zone, 3) Difference in total risk between each pair of zones, 4) Edge/node removal, 5) Edge capacity restriction, 6) Distance between hazmat vehicles, 7) Dissimilarity measures, 8) Routes overlap, 9) Distance to vulnerable centers, and 10) Risk equity index
	Structural constraints	1) Flow conservation constraints, 2) Number of vehicles available, 3) Time-window constraints, 4) Excluding undesirable routes (too close to population), 5) Inaccessible roads, 6) Limiting total network consequences, 7) Limiting total network risk, 8) Limiting the risk of the route, 9) Limiting accident probability of route, 10) Limiting total consequence of a route, 11) Limiting probability of no-accident for each route, 12) Limiting capacity of routes, 13) Limiting length of the route, 14) Limiting route duration, 15) Shipment suspension, 16) Subtour elimination, 17) Vehicles capacity, 18) Dispatching constraints, 19) Budget constraint, 20) Signal setting constraints for intersections, 21) Limiting the number of allowable trips during a planning horizon, and 22) Maximum toll level
Decisions	Routing	
	Scheduling	
	Network design	1) Link restriction (general), 2) Link restriction for each OD pair, 3) Link restriction for each type of hazmat, 4) Time-dependent link restriction, 5) Link's capacity limitation, 6) Toll (general), 7) Toll for each type of hazmat, 8) Toll on terminals, 9) Lane reservation, and 10) Signal setting
	Congestion	1) With queue discipline and 2) Without queue discipline
	Vehicle	1) Fleet assignment and 2) Fleet planning
Parameters	Common	1) Link's travel cost (i.e., economic costs ($), travel time, and Length), 2) Incident probability (i.e., known or unknown), 3) Network demand,4) Link's population loss, 5) Node's population loss, 6) Weather condition, 7) Links traffic flows, 8) Accident severity, and 9) Incident probability (i.e., Known or Unknown)
	Particular	1) Track condition, 2) Vehicle damage costs, 3) Cargo damage costs, 4) Cleanup costs, 5) Evacuation costs, 6) Insurance cost, and 7) Node's service time
Objectives	Economic	1) Total monetary costs ($), 2) Total travel time, 3) Total route length, 4) Maximum travel time, 5) Toll costs, and 6) Total general cost
	Environmental	1) Carbon emission
	Social: Risk	*Min*: 1) Expected risk, 2) Population exposure, 3) Conditional probability, 4) Incident probability, 5) Perceived risk, 6) Mean variance, 7) Disutility function, 8) Value-at-risk (VaR), 9) Conditional value at risk (CVaR), and 10) Load dependent risk *Min*-max: 1) Risk among routes,
	Social: Equity	*Min*: 1) Edge capacity, 2) Dissimilarity measures, and 3) Routes overlap *Max*: 1) Risk equity index and 2) Restricted risk equity index *Min*-max: 1) Risk among links, 2) Risk among zone and 3) Risk difference between each pair of zones *Max*-min: 1) Distance to vulnerable centers and 2) Distance between hazmat vehicles
	Others	Min: 1) Lost profit, 2) Accident rates, 3) Number of vehicles, 4) Total shipment delay, and 5) Total impact of lane reservation on normal traffic
Modeling/Solution technique	Simple formulation	1) Link-based and 2) Route-based
	Multi-player game	Demon approach with two players (government vs. carrier) under Nash or Stackelberg games
	Exact	
	Heuristic	
	Metaheuristic	1) Genetic algorithm (GA), 2) Tabu search (TS), 3) Memetic algorithm (MA), 4) Simulated annealing (SA), 5) Differential evolution (DE), 6) Particle swarm optimization (PSO), 7) Variable neighborhood search (VNS), and 8) Non-dominated sorting GA-II (NSGA-II)
	Hybrid	
Case study	Data source	1) Real-life case, 2) Randomly generated, and (3) Online database
	Type of case	1) Real and 2) Hypothetical
	Zone of case	1) Country and 2) City
	Size of case	Number of 1) Nodes, 2) Links, 3) Routes, and 4) Customers
	Largest instance size	Number of 1) Nodes and links and 2) Customers

2.2. Quantitative measures in hazmat transportation problems

In the reviewed articles, several *economic*, *environmental*, and *social* measures have been used to form the objectives (or formally objective functions) and the constraints when modeling a hazmat transportation problem. In terms of *economic* measures, carriers, as the main players in hazmat transportation, usually prioritize the minimization of monetary objectives to other environmental and social objectives. On the other hand, the government as another player can seek different economic, environmental, and social objectives, where both environmental and social measures are usually translated into monetary measures. For instance, minimizing the total fatal and injury costs as an economic objective also fulfills social objectives. From the carriers' perspective, these measures include total travel time in the network with/without delay in intersections or waiting points, total travel distance in the network, total monetary routing costs including travel and toll costs, fixed costs including insurance, inbound and outbound drayage, equipment acquisition, vehicle purchase, and rental costs, indemnification costs including cleanup, environmental, population exposure costs, and scheduling costs including delay costs in the delivery of products and holding and shortage costs. From the governmental aspect, these measures normally include population exposure, cleanup, environmental, and infrastructure development costs.

In comparison to the *economic* and *social* measures, the contribution to *environmental* measures in the related literature is low. Many researchers have reflected the environmental concerns by minimizing monetary environmental costs, where only Teoh, Ponnambalam and Subramanian (2016) proposed a pure environmental measure by minimizing the carbon emissions as an objective function.

Among all three types of measures, *social* measures have been the most important ones when studying hazmat transportation problems, particularly HR, HRS, and HTND problems. These measures are usually defined in a manner to either reduce the impact of hazmat incidents on the population (i.e., risk) or spread it fairly among all groups of society (i.e., equity). In hazmat transportation problems, the risk is a function of incident probability and its consequences; it is normally calculated along an edge or a route. In HR, HRS, and HTND problems, the risk along a route is used more frequently than the risk along an edge. In this study, we identified twelve different *risk* measures in the related literature. A summary of the risk measures including their definitions, equations, advantages, and limitations is provided in Table 5, where the notations are defined at the end of the table.

Equity measures are the second most studied social measure in hazmat transportation problems. Some of the risk measures identified in Table 5, including maximum risk, mean-variance, and expected disutility, can also be considered as equity measures when they are used as objective functions or constraints in the model (Khezerlou, Vahdani & Yazdani, 2021). For instance, Bianco, Caramia and Giordani (2009) and Bianco, Caramia, Giordani and Piccialli (2015) have investigated equity in their models by minimizing the maximum risk imposed to the population around the network's links. In this paper, we have identified a set of other equity measures in the literature, which are independent of the presented risk measures. These measures are the following:

- **Edge capacity restriction –** It prevents hazmat traffic overloading on certain links of the network; hence, an almost even distribution of hazmat shipments occurs among a majority of the links (Iakovou et al., 1999; Ma, Cheang, Lim, Zhang & Zhu, 2012).
- **The difference in the total risk between each pair of zones –** It is a simple measure that accounts for the difference of the total risk rate imposed on each pair of zones. Gopalan, Kolluri, Batta and Karwan (1990) and Kang, Batta and Kwon (2014a) limited this risk to a threshold to provide equity in the network. Lindner-Dutton, Batta and Karwan (1991) proposed three different equity measures in this regard. They defined m_t as the maximum difference between the cumulative risk of two zones after t trips. Accordingly, the first measure is the sum of m_t for all t, while the second measure is the maximum m_t for all t, and the third measure is a linear combination of the two measures.
- **Edge/node removal***:* Frank, Thill and Batta (2000) studied the HR problem between long-distanced OD pairs through a working spatial decision support system (SDSS) that allows decision-makers to temporally remove certain links of the network or some intersections from the routing process, particularly those located near to highly populated urban areas. They claimed that this approach not only decreases the solution run time but also holds equity in spreading the hazmat risk incidents throughout the network.
- **Dissimilarity measure***:* Dell'Olmo, Gentili and Scozzari (2005) and Martí, Luis González Velarde and Duarte (2009) introduced the concept of determining dissimilar routes, especially in HR problems. By equally distributing the total risk among the routes, they proposed a two-phase approach: 1) a set of non-dominated routes between an OD pair is selected by implementing a multi-criteria shortest path algorithm and 2) for each selected route, a buffer zone approximating the impact area of a hazmat incident is considered. According to the areas of buffer zones and their intersection, the dissimilarity is then calculated. After Dell'Olmo et al. (2005), Carotenuto, Giordani and Ricciardelli (2007a) proposed another dissimilarity index as a developed version of what has been proposed by Erkut and Verter (1988), where in addition to the common links of routes, the links that are very close to each other are also counted as the similarity between routes.
- **Routes overlap –** Minimizing or bounding the overlapping rate between a pair of routes can contribute to spreading the risk and holding the equity in the network. Dadkar, Jones and Nozick (2008) considered this rate between the selected routes as a minimization objective function.
- **Risk equity index (EI) –** Carotenuto et al. (2007a) proposed the EI as the variation coefficient for risk to the population around the links of the network as an equity measure. Fontaine, Crainic, Gendreau and Minner (2020) proposed several equilibrium risk measures similar to the EI based on the average or the maximum risk deviations imposed on the population nodes.
- **Restricted risk equity index (REI) –** Carotenuto et al. (2007a) proposed another equity measure similar to EI, named REI. Since the EI encompasses all links of the network including the links far from the selected routes, its value is high; hence, the authors revised the EI to only calculate the risk deviation for the set of links that belong to the selected routes**.**
- **Distance between hazmat vehicles:** It assures the safety between two consequent hazmat vehicles at any given time. Accordingly, Carotenuto, Giordani, Ricciardelli and Rismondo (2007b) considered a set of buffer zones around the vehicles to prevent any probable contact. Wang, Zhang, Che and Jiang (2018) provided this distance by imposing a waiting time between the vehicles carrying the hazmat commodities.
- **Risk on each link or zone –** In the studies of Fang, Ke and Verma (2017), Zhou, Chu, Che and Zhou (2013), and Garrido and Bronfman (2017), the risk on each link or zone has been applied as an equity measure by limiting it to an acceptable level. Fang et al. (2017) and Zhou et al. (2013) limited the risk among the links of the network while Garrido and Bronfman (2017) limited the risk within a zone.
- **Maximizing the minimum distance to vulnerable centers –** Bronfman, Marianov, Paredes-Belmar and Lüer-Villagra (2016) introduced a new technique to hold equity in the network. Their approach is based on minimizing the maximum danger posed to the vulnerable centers due to the presence of hazmat vehicles. The magnitude of the imposed danger is related to both the population nodes and the minimum distance between the populated nodes and hazmat vehicles.

3. Classification of HR problems

The HR problem was first introduced by Abkowitz and Cheng (1988) and Batta and Chiu (1988). Although this problem can be studied as a part of HRS, HLR, and HTND problems, this section focuses only on pure HR problems. In general, the HR problem deals with selecting single (multiple) optimal route(s) to ship/distribute hazmat between single/multiple OD pairs targeting different objectives subject to a set of constraints. In practice, the HR problem can be formulated in two different ways: (1) routing the hazmat between a single OD pair or multiple OD pairs, which are also called hazmat *local* and *global* routing problems, respectively (Erkut et al., 2007), and (2) distributing the hazmat from single/multiple depots to multiple customers (Hamdi-Dhaoui, Labadie & Yalaoui, 2014; Kheirkhah et al., 2016b; Teoh et al., 2016; Timajchi, Al-e-Hashem & Rekik, 2019). In this regard, Holeczek (2019) introduced

Table 5
. Risk measures in hazmat transportation problems.

Measure	Definition	Mathematical expression	Advantages	Limitations	First Ref.
Incident probability	Total incident probabilities on edges along route l	$\sum_{(i,j)\in A^l} p_{ij}$	Simple without the need for too much data	It may generate biased outputs due to considering only incident consequences	Saccomanno and Chan (1985)
Population exposure	Total incident consequences on edges along route l	$\sum_{(i,j)\in A^l} c_{ij}$	Simple without the need for too much data	It may generate biased outputs due to considering only incident consequences	ReVelle, Cohon and Shobrys (1991)
Expected risk (traditional risk)	The total product of all incident probabilities and consequences on edges along route l	$\sum_{(i,j)\in A^l} p_{ij}c_{ij}$	Simple, with minimum data, an incident along earlier edges of a route trip does not terminate a hazmat trip	It has a risk-neutral attitude because of the small probabilities of high consequence events	Alp (1995)
Perceived risk	Similar to the expected risk measure but edges consequences are of power q ($q \geq 1$)	$\sum_{(i,j)\in A^l} p_{ij}(c_{ij})^q$	Has a risk aversion attitude because of intensifying the importance of incident consequences	It is difficult to adjust parameter q	Abkowitz, Lepofsky and Cheng (1992)
Maximum risk	Maximum edge risk (population exposure) along route l	$\max_{(i,j)\in A^l} c_{ij}$	Has a risk aversion attitude and is suitable for catastrophic avoidance approaches	It is too pessimistic	Erkut and Ingolfsson (2000)
Mean-variance	Total expected risk and the variance of the number of affected people on edges along route l	$\sum_{(i,j)\in A^l} (p_{ij}c_{ij} + \theta p_{ij}(c_{ij})^2)$	Has a risk aversion attitude and is suitable for catastrophic avoidance approaches	Difficulties in calculating the mean and variance of incidents consequences from limited real data	Erkut and Ingolfsson (2000)
Expected disutility	Similar to the expected risk but instead of an edge's consequence, an exponential disutility function is considered	$\sum_{(i,j)\in A^l} p_{ij}(e^{(\theta c_{ij}-1)})$	The exponential function for consequences makes it suitable for a risk aversion attitude	Similar to perceived risk, it is difficult to adjust parameter θ	Sivakumar and Batta (1994)
Conditional probability	Expected risk per total incident probabilities of edges along route l	$\sum_{(i,j)\in A^l} p_{ij}c_{ij} / \sum_{(i,j)\in A^l} p_{ij}$	Suitable for catastrophic events (i.e., low probability and high consequence)	Increasing incident probability on a link may reduce the conditional risk of a route that includes the link	Sivakumar, Batta and Karwan (1993)
VaR	Minimum risk level β where the probability of route's risk more than β is less than or equal to $(1-\alpha)$	$VaR^l_\alpha = \min\{\beta : \Pr\{R^l \geq \beta\} \leq 1-\alpha\}$	Covers different risk attitudes from risk-neutral to risk aversion attitudes and is flexible to accommodate various practical factors	Has a risk-neutral attitude and may lead to an inaccurate risk perception where low-probability-high-consequence events may be ignored	Kang, Batta and Kwon (2014a,b)
CVaR	The expected value of the risk that is greater than or equal to the VaR value at a given confidence level α	$CVaR^l_\alpha = \min_{\gamma\geq 0}[\gamma + \frac{1}{1-\alpha}\sum_{(i,j)\in A^l} p_{ij}[c_{ij}-\gamma]^+]$	Provides a risk aversion attitude and is a tractable and coherent risk measure	It is too complex	Toumazis and Kwon (2013)
Actual load-dependent risk	The risk of passing a link depends on the volume of hazmat on the link (y_{ij}), damage per unit amount of hazmat k (s^k), population exposure (Pop_{ij}), incident probability (p_{ij}), conditional probability for a leakage given the incident (p'_{ij}), and impact of the specific day on incident probability (ω_{ij})	$p_{ij}p'_{ij}\omega_{ij}(Pop_{ij}s^k y_{ij})$	In some situations, although the total risk is insignificant, the risk of a specific vehicle may be very high. Therefore, the measure can evaluate each vehicle's risk closed to the reality	Needs more parameters than other measures and is useful only for calculating risk over the links	Zhang, Wang, He, Yang and Guan (2018)
Population-based risk	The calculating risk posed to population nodes rather than network's arcs	$R_c(x) = p_c \sum_{m\in M}\sum_{k\in K}\sum_{(i,j)\in A} l^{mkc}_{ij}\sigma^{km}_{ij}x^{km}_{ij}\phi_k$	It is simple and critical population nodes such as schools or hospitals can be prioritized	Has unique application when multiple modes exist and the equity matters	Fontaine et al. (2020)

Notations: (i,j): Link between nodes i and j in the network, A: Set of links in the network, A^l: Set of links belonging to route l, p_{ij}: Incident probability over the link (i,j), c_{ij}: Incident consequence over the link (i,j), R^l: The risk of route l, p_c: Population at node c, $l^{mkc}_{ij}\sigma^{km}_{ij}x^{km}_{ij}$: Accident risk at node c by hazmat type k transported via mode m link (i,j), ϕ_k: Population influence factor, and θ, q, r: Adjustment parameters (e.g., r is equal to VaR^l_α).

the former way of formulation as the *shortest path problem* and the latter as the *vehicle routing problem* in HR problems. Indeed, combining hazmat local and global routing problems into a single category (i.e., shortest path problem) can be assumed as a drawback of this classification since these problems display different properties. In this paper, we accordingly classify the HR problems into three categories as follows:

- *Hazmat local routing problems* (i.e., transporting hazmat between a single OD pair).
- *Hazmat global routing problems* (i.e., transporting hazmat between multiple OD pairs).
- *Hazmat vehicle routing problems* (i.e., transporting/distributing hazmat from single/multiple depots to multiple customers).

In the following, we classify the reviewed articles studying HR problems in the literature from an OR viewpoint, including assumptions, objectives and constraints, decisions, input parameters, type of modeling, solution techniques, and case studies.

3.1. Assumptions

The assumptions of an HR problem in the related literature are listed in Table 6 that classifies the papers based on different characteristics such as the employed transportation mode, the structure of the OD nodes (i.e., single/multiple origins/depots and single/multiple customers), the involved players (i.e., carriers, government, others) and their type of the competition, the type of the vehicle (i.e., homogenous/heterogeneous) to transport the hazmat, the time horizon (i.e., single/multiple periods), and finally the classes of hazmat (i.e., single/multiple classes).

As can be observed in Table 6, most of the papers dealing with HR problems focus on the road and rail modes of transportation (77% and 13% of articles, respectively). The reason can be attributed to both the availability and simplicity of transportation by the road and rail modes (i.e., easier loading, unloading, and processing operations compared to air and water ways) as well as the relevance of road and rail modes of transportation when designing routing models. Conversely, few papers have considered the multimodal and maritime modes of transportation. A typical reason for a lower number of studies on intermodal modes of transportation might be that research works typically start with the simpler case (i.e., single mode of transportation) before including complexity. One may note, however, that the multimodal mode of transportation has gained popularity in the study of HR problems since 2010, with a major focus on rail-truck connections. Besides, only a single paper was found considering the maritime mode, published in 1999, and no study was found on air transportation despite its frequent real-world applications.

In terms of the structure of the HR problem, the respective popularity of local, global, and vehicle routing problems, in terms of the number of papers, has been 50, 33, and 17%. These problems have also been popular in particular periods. For instance, the most popular HR problems from 1983 to 2009, from 2009 to 2016, and from 2016 to 2020 have been hazmat local, global, and vehicle routing problems with shares of 77%, 69%, and 55%, respectively. This shows that hazmat vehicle routing problems with single or multiple depots have been gaining attention in recent years.

The statistics on the problem's players show that the main players (decision makers) in HR problems are the carriers (92% of articles). The reason is that the carriers absorb the highest risk of transportation and they are probably the main ones responsible for hazmat incidents. Accordingly, HR problems should be mostly modeled from the carrier's point of view. Most of the articles published before 2009, nearly 96% of articles, have considered a homogenous fleet, while the number of studies assuming heterogeneous fleets has increased since 2009. This seems reasonable since carriers may have different vehicles with different capacities and the risk of hazmat incidents on a link becomes a function of the hazmat volume in the vehicle. Table 6 also reveals that only 8% of articles have studied multi-period HR problems, which is somewhat reasonable because tackling a routing problem in a multi-period context without scheduling amounts to solving a sequence of single-period routing problems. It is worth mentioning that, due to the increase in the demand and class (type) of hazmat, carriers are responsible to carry more than a single class of hazmat shipments, while only 7 papers (13% of the articles) have studied HR problems with multiple hazmat classes. Accordingly, studying HR problems with multiple classes of hazmat is an emerging need for carriers, which should be addressed more as a future research direction. Furthermore, the literature lacks studies investigating the effect of competition or collaboration between several carriers (players) based on different objectives (particularly cost and risk) in all three worldwide, inter-regional, or intra-regional scales; hence, this could be an interesting future research direction.

3.2. Objectives and constraints

Many stakeholders, such as freight forwarders (i.e., carriers or dispatchers), governments, insurers, environmentalists, and emergency responders, affect, directly or indirectly, the objectives of any HR problem in different ways. Accordingly, the HR problem is normally a multi-objective problem, where minimizing risk and cost of transportation are among the most important objectives. This section scrutinizes the literature on the HR problems based on their objectives and constraints.

The major objectives and constraints considered in the HR literature are presented in Tables 7 and 8, respectively. Based on the number of objectives, Table 7 classifies the articles into single-objective (SOP) or multi-objective problems (MOP). At the end of both Tables 7 and 8, practical and useful technical notes on some of the papers are provided as *comments*.

According to Table 7, it is evident that a considerable number of studies consider risk and economic objectives compared to equity goals when designing an HR model. Accordingly, the lack of environmental and equity objectives in HR problems is evident. This is not surprising since the carriers, as the main players of the problem, mostly look for controlling the hazmat risk imposed to the environment and the hazmat transportation cost. Indeed, it is the government's responsibility to seek the environmental and equity objectives by forcing the carriers to respect the environmental and equity concerns.

In terms of risk-related objectives, nearly 77% of the literature has aimed at minimizing expected risk or population exposure as single objectives since they are the most straightforward risk measures to control in HR problems. In this regard, the application of other risk-related objectives, such as mean-variance, disutility function, CVaR, and VaR measures, particularly in multi-objective HR problems, could be an interesting future research direction. Considering the economic objective of carriers, Table 7 also reveals that up to 90% of the literature have targeted monetary objective functions and that only a few papers have modeled it through minimizing total travel time/length. The latter category of papers assumes that travel cost may not well reflect the risk of a hazmat shipment due to the time that a shipment spends in transportation (i.e., travel time and waiting time in transit yards). Indeed, the higher the waiting/travel time of a hazmat shipment, the higher the risk of a hazmat incident due to external factors.

An overall view on Tables 7 and 8 explains that nearly one-third of the literature on HR problems contains risk equity objectives or constraints, where modeling risk equity by constraints

Table 6
Classification of articles studying HR problems based on their assumptions.

Reference	Transportation mode	Problem structure				Model players			Players competition	Vehicle type		Multi/Single period	Multi/single hazmat classes
		Local routing	Global routing	Vehicle routing		Carrier	Government	Others		Homogenous	Heterogeneous		
				Single depot	Multiple depots								
Glickman (1983)	Rail	–	√	–	–	–	√	–	–	√	–	S	S
Abkowitz and Cheng (1988)	Road	–	√	–	–	√	–	–	–	–	√	S	M
Batta and Chiu (1988)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Gopalan et al. (1990)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Klein (1991)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Lindner-Dutton et al. (1991)	Road	–	√	–	–	√	–	–	–	√	–	S	S
Wijeratne, Turnquist and Mirchandani (1993)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Beroggi (1994)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Patel and Horowitz (1994)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Beroggi and Wallace (1995)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Karkazis and Boffey (1995)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Jin, Batta and Karwan (1996)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Jin and Batta (1997)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Nembhard and White Iii (1997)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Sherali et al. (1997)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Verter and Erkut (1997)	Road	√	–	–	–	√	√	–	–	√	–	S	S
Marianov (1998)	Road	√	√	–	–	√	–	–	–	√	–	S	S
Iakovou et al. (1999)	Maritime	–	√	–	–	√	–	–	–	√	–	S	M
Nembhard and White Iii (1999)	Road	√	–	√	–	√	–	–	–	√	–	S	S
Erkut and Ingolfsson (2000)	Road	–	–	√	–	√	–	–	–	√	–	S	S
Frank et al. (2000)	Road	√	–	–	–	√	–	–	–	√	–	M	S
Dell'Olmo et al. (2005)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Serafini (2006)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Carotenuto et al. (2007a)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Glickman et al. (2007)	Rail	–	√	–	–	√	–	–	–	√	–	S	S
Dadkar et al. (2008)	Road	√	–	–	–	√	–	–	–	√	–	M	S
Martí et al. (2009)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Verma (2009)	Rail	–	√	–	–	√		RA*	–	–	√	S	M

(*continued on next page*)

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Table 6 (*continued*)

Reference	Transportation mode	Problem structure				Model players			Players competition	Vehicle type		Multi/Single period	Multi/single hazmat classes
		Local routing	Global routing	Vehicle routing		Carrier	Government	Others		Homogenous	Heterogeneous		
				Single depot	Multiple depots								
Verma and Verter (2010)	MI[a]	–	√	–	–	√	–	–	–	√	–	S	S
Lozano, Muñoz, Macías and Antún (2011)	Road	–	√	–	√	√	–	–	–	√	–	S	S
Verma et al. (2011)	Rail	–	√	–	–	√		RA	–	√	–	S	S
Verma et al. (2012)	MI*	–	√	–	–	√	√	–	–	√	–	S	S
Hamdi-Dhaoui et al. (2014)	Road	–	–	√	–	√	–	–	–	√	–	S	M
Kang et al. (2014a)	Road	–	√	–	–	√	√	–	–	√	–	S	M
Kang et al. (2014b)	Road	√	–	–	–	–	–	–	–	–	–	S	S
Assadipour et al. (2015)	MI[a]	–	√	–	–	√	–	–	–	√	–	S	S
Bronfman, Marianov, Paredes-Belmar and Lüer-Villagra (2015)	Road	√	–	–	–	–	√	–	–	√	–	S	S
Fan et al. (2015)	Road	–	√	–	–	√	–	–	–	-	√	S	S
Bronfman et al. (2016)	Road	–	√	–	–	√	√	–	–	√	–	S	S
Kheirkhah et al. (2016b)	Road	–	–	√	–	√	–	–	–	√	–	S	S
Teoh et al. (2016)	Road	–	–	√	–	–	√	–	–	√	–	S	S
Toumazis and Kwon (2016)	Road	√	–	–	–	√	–	–	–	√	–	S	S
Zhao and Zhu (2016)	Road	–	–	–	√	√	–	–	–	√	–	S	S
Garrido and Bronfman (2017)	Road	√	–	–	–	√	–	–	–	√	–	S	M
Hosseini and Verma (2017)	Rail	√	–	–	–	√	–	–	–	–	√	S	S
Hosseini and Verma (2018)	Rail	√	–	–	–	√	–	–	–	–	√	S	S
Kumar et al. (2018)	Road	–	√	–	–	√	–	–	–	–	√	S	M
Timajchi et al. (2019)	Road	–	–	√	–	√	–	S*	–	-	√	M	S
Wang et al. (2018)	Road	–	–	√	–	√	–	–	–	√	–	S	S
Zhang et al. (2018)	Road	–	–	√	–	√	–	–	–	√	–	S	S
Ke (2020)	MI	–	√	–	–	√	–	–	–	√	–	M	S
Hosseini and Verma (2021)	Rail	–	√	–	–	√	–	RA	–	–	√	S	S
Statistics (%)	Road: 77****Rail: 13****MI: 8****Maritime: 2	50	33	14	3	92	13	8	0	85	15	S: 92****M: 8	S: 87****M: 13

* MI: Multimodal or Intermodal (Rail-Truck), RA: Regulatory agencies, S: Supplier.

Table 7
Classification of articles studying HR problems based on their objectives.

Main objectives		Objectives: SOP or MOP
Risk (Min)	Expected risk	SOP: Glickman (1983), Batta and Chiu (1988), Gopalan et al. (1990), Patel and Horowitz (1994), Karkazis and Boffey (1995), Jin et al. (1996), Jin and Batta (1997), Carotenuto et al. (2007a) MOP: Abkowitz and Cheng (1988), Nembhard and White Iii (1997), Iakovou et al. (1999), Serafini (2006), Glickman et al. (2007), Dadkar et al. (2008), Verma (2009), Fan et al. (2015), Bronfman et al. (2016), Teoh et al. (2016), Timajchi et al. (2019)
	Population exposure	SOP: Batta and Chiu (1988), Klein (1991) MOP: Verma and Verter (2010), Lozano et al. (2011), Verma et al. (2011), Verma et al. (2012), Assadipour et al. (2015), Ke (2020)
	Conditional probability	SOP: Sherali et al. (1997), Garrido and Bronfman (2017)
	Incident probability	MOP: Marianov (1998), Dell'Olmo et al. (2005), Zhao and Zhu (2016)
	Maximum risk	SOP: Erkut and Ingolfsson (2000) MOP: Wang et al. (2018)
	Mean-variance	SOP: Erkut and Ingolfsson (2000)
	disutility function	SOP: Erkut and Ingolfsson (2000)
	CVaR	SOP: Toumazis and Kwon (2016), Hosseini and Verma (2018), Hosseini and Verma (2021)
	VaR	SOP: Kang et al. (2014a), Kang et al. (2014b), Hosseini and Verma (2017)
	Load dependent risk	MOP: Zhang et al. (2018)
	General	MOP: Beroggi (1994), Beroggi and Wallace (1995), Nembhard and White Iii (1999)
Equity	Min: Risk difference between each pair of zones	SOP: Lindner-Dutton et al. (1991)
	Min: Dissimilarity measure	MOP: Dell'Olmo et al. (2005), Martí et al. (2009)
	Min: Routes overlap	MOP: Dadkar et al. (2008)
	Max: Minimum distance to vulnerable centers	MOP: Bronfman et al. (2015), Bronfman et al. (2016)
Economic & Environmental (Min)	Total transportation costs ($)	SOP: Verter and Erkut (1997), Kumar et al. (2018) MOP: Abkowitz and Cheng (1988), Wijeratne et al. (1993), Beroggi (1994), Beroggi and Wallace (1995), Marianov (1998), Iakovou et al. (1999), Verma (2009), Verma et al. (2011), Verma et al. (2012), Hamdi-Dhaoui et al. (2014), Assadipour et al. (2015), Bronfman et al. (2015), Zhao and Zhu (2016), Timajchi et al. (2019), Wang et al. (2018), Zhang et al. (2018), Ke (2020)
	Total travel time	SOP: Frank et al. (2000) MOP: Wijeratne et al. (1993), Bronfman et al. (2016), Ke (2020)
	Total route length	MOP: Nembhard and White Iii (1997), Nembhard and White Iii (1999), Dell'Olmo et al. (2005), Serafini (2006), Glickman et al. (2007), Dadkar et al. (2008), Martí et al. (2009), Lozano et al. (2011), Fan et al. (2015)
	Total general cost	MOP: Verma and Verter (2010)
	Lost profit	SOP: Kheirkhah et al. (2016b)
	CO_2 emission	MOP: Teoh et al. (2016)

***Technical comments*:** Expected risk in Glickman (1983) is a function of hazmat traffic volume, population exposure, rail track condition, and accident rate and severity. Klein (1991) identified the shortest path with respect to three fuzzy sets, safety in links, population exposure, and safety in intersections. Beroggi (1994) and Beroggi and Wallace (1995) introduced ordinal preferences on risk and cost (low risk, high cost, and high risk) and maximized users' preferences to find the best routes, where the risk was transformed to cost as life-saving cost. Jin et al. (1996) proposed two HR models, where the models' objectives were total expected risk and expected risk per trip. Moreover, in the first model, the shipping of hazmat is ceased when the number of accidents exceeds a threshold or the total shipments are moved; while, in the second model, the shipping of hazmat is ceased only when the number of accidents exceeds a threshold. Jin and Batta (1997) proposed six extensions of the expected risk measure as the HR model's objective as 1) expected risk, 2) expected risk with shipment ceasing after occurring t accidents or T movements, 3) expected risk with shipment ceasing after occurring t accidents, 4) objective 3 with changing the parameters of the model after each accident, 5) expected risk per trip with shipment ceasing after occurring t accidents, and 6) expected number of trips done between two successive accidents. Erkut and Ingolfsson (2000) proposed maximum risk, mean-variance risk, and expected disutility function as objectives. However, rather than minimizing the maximum risk, they minimized the total accident probability and bounded the total consequences through the model's constraints. Dell'Olmo et al. (2005) proposed a HR model in two phases. In the first phase, the risk and length of the routes are minimized and consequently, a set of Pareto-optimal routes is identified. In the second phase, through minimizing a dissimilarity function, the optimal routes are selected from the set of Pareto-optimal routes. Toumazis and Kwon (2016) proposed two HR models, where minimizing the CVaR measure and the worse-case CVaR (WCVaR) are the objectives of the first and the second models, respectively. The WCVaR is a developed form of the CVaR measure in which the incident consequence and its probability are uncertain. Ke (2020) proposed a bi-objective HR model in which the first objective minimizes total transportation, disruption, terminal capacity expansion, fixed, and delay costs while the second objective minimizes total risk.

is more popular than by objectives. By looking at the non-equity constraints in the reviewed papers, it can be seen that most of them are designed toward restricting the number of populations exposed to hazmat risks. In this regard, a considerable number of studies (up to 27%) have focused on hazmat routes and controlled the risk by excluding undesirable routes (too close to population) or limiting route length, hazmat risk, consequences, and incident probability. There are also few articles (Batta & Chiu, 1988; Erkut & Ingolfsson, 2000; Glickman, Erkut & Zschocke, 2007; Fan, Chiang & Russell, 2015) that control the risk on a link or network levels by either making some links inaccessible or bounding the total network's risk or consequences. Other common constraints, which are not associated with hazmat risk or equity, are fleet size, vehicle capacity, and time-window constraints.

3.3. Parameters and decisions

This section classifies the reviewed papers studying HR problems based on the incorporated parameters and decisions as Tables 9 and 10, respectively. The classification of parameters (Table 9) helps the readers to identify what and which types of parameters have been used to model the problem. The classification of the decisions (Table 10) provides the readers with a set of decisions other than the main routing decisions in HR problems. It helps to have a better understanding of how the main routing decisions can be coupled with other decisions to develop a more realistic HR model.

Based on Table 9, the parameters are mainly categorized into link-related parameters (e.g., link's travel costs, link's population

Table 8
Classification of articles studying HR problems based on their constraints.

Main constraints		References
Constraints for providing equity	Risk on each link	Abkowitz and Cheng (1988), Beroggi (1994), Beroggi and Wallace (1995), Carotenuto et al. (2007a), Hosseini and Verma (2021)
	Risk on each zone	Garrido and Bronfman (2017)
	The difference in total risk between each pair of zones	Gopalan et al. (1990), Kang et al. (2014a)
	Edge/node removal	Frank et al. (2000)
	The capacity of the network's links	Iakovou et al. (1999)
	Distance between HAZMAT vehicles	Wang et al. (2018)
Number of vehicles available		Verma (2009), Verma et al. (2012), Kheirkhah et al. (2016b), Teoh et al. (2016), Zhao and Zhu (2016, Hosseini and Verma (2017, Hosseini and Verma (2018), Hosseini and Verma (2021)
Time-window constraints		Verma and Verter (2010), Verma et al. (2012), Assadipour et al. (2015), Fan et al. (2015), Ke (2020)
Excluding undesirable routes (too close to population)		Batta and Chiu (1988)
Inaccessible roads		Batta and Chiu (1988), Fan et al. (2015)
limiting total network consequences		Erkut and Ingolfsson (2000)
Limiting total network risk		Glickman et al. (2007)
Limiting the risk of routes		Jin et al. (1996), Jin and Batta (1997), Sherali et al. (1997), Frank et al. (2000), Garrido and Bronfman (2017)
Limiting accident probability of routes		Jin et al. (1996), Jin and Batta (1997), Frank et al. (2000), Garrido and Bronfman (2017)
Limiting total consequence of routes		Sherali et al. (1997), Frank et al. (2000)
Limiting probability of no-accident for each route		Marianov (1998)
Limiting the length of routes		Frank et al. (2000)
Shipment suspension		Jin et al. (1996), Jin and Batta (1997)
Sub-tour elimination		Sherali et al. (1997)
Vehicles capacity		Kheirkhah et al. (2016b), Teoh et al. (2016), Zhao and Zhu (2016), Wang et al. (2018), Zhang et al. (2018)

***Technical comments*:** Both bridges and tunnels are not allowed to be a part of the hazmat routes in Batta and Chiu (1988) through the model's constraints. Beroggi (1994) and Beroggi and Wallace (1995) bounded the generated preference for traveling on a link (based on the cost and the risk of traveling on the link) to a threshold. Jin et al. (1996) and Jin and Batta (1997) ceased the shipments moving once several incidents occur in the network. Marianov (1998) proposed three constraints on risk (bounding overall risk in the network, risk of each OD pair, and risk of each link), without applying them in the proposed model. Verma (2009) considered three specific constraints for modeling a rail HR problem: the capacity of each train service type, the capacity of each classification yard, and the capacity of each transfer yard. The constraints on limiting the capacity of each yard also exist in Verma and Verter (2010). Fan et al. (2015) considered a closure time window for a set of links. Kheirkhah et al. (2016b) limited the budget of the interdictor, interdicting links and playing a Nash game with carriers. Zhao and Zhu (2016) proposed a hazmat vehicle routing problem for recycling the explosive waste and limited the capacity of waste collection centers located at the beginning and the end of each vehicle trip. Hosseini and Verma (2021) provided equity by limiting expected hazmat consequences on rail network arcs and yards by some thresholds. Ke (2020) considered a set of new constraints on the capacity of disrupted and normal terminals as well as on the required time for passing through disrupted terminals and paths.

loss, and link's traffic flow), network-related parameters (e.g., node's demand and node's population), and incident-related parameters (e.g., incident rate, incident probability, and accident severity). Furthermore, the type of these parameters can be deterministic (DE), stochastic (ST), dynamic (DY), probabilistic (PR), possibilistic (PO), and real-time (RE). As it can be observed from Table 9 that network demand, link population loss, and incident probability are the fundamental parameters when modeling an HR problem. Indeed, they are the main parameters to estimate the risk of hazmat incidents on the transportation routes. Along with the parameters elaborated in Table 9, there are other important parameters that no paper in the literature has incorporated in the modeling of an HR problem including the characteristics of hazmat vehicles (e.g., age, speed limit, and load capacity), while they directly affect the consequences upon a hazmat incident. Furthermore, the issue of considering an unknown probability of an incident in HR problems has not been investigated yet. Regarding the type of the parameters, the link's travel cost ($), network demand, node's population loss, link's traffic flows, and accident severity are always deterministic. Although uncertainty increases the model complexity, considering the network demand and link's travel cost ($) under uncertainty could be more realistic and it would be a promising future research direction.

Table 10 indicates that, among different decisions, fleet assignment, congestion-controlling decisions with/without queue discipline (Karimi-Mamaghan, Mohammadi, Pirayesh, Karimi-Mamaghan & Irani, 2020a; Karimi-Mamaghan, Mohammadi, Jula, Pirayesh & Ahmadi, 2020b; Mohammadi, Jula & Tavakkoli-Moghaddam, 2019b; Mohammadi, Dauzère-Pérès & Yugma, 2019a; Mohammadi, Dauzère-Pérès, Yugma & Karimi-Mamaghan, 2020), and fleet planning are the most popular decisions taken when modeling an HR problem. The idea behind taking the congestion of hazmat into account is that the higher the congestion of hazmat on routes or transit yards, the higher the risk of hazmat incidents. In addition, higher congestion in transit yards results in delays in processing (transiting) the hazmat and this delay itself increases the risk of disruption.

Apart from the routing and elaborated decisions in Table 10, the decision on the transportation mode (particularly for routing in intermodal and multimodal transportation) or packing the hazmat with different classes in the vehicles, trains, vessels, or cargo planes are among other interesting decisions that can be investigated through future studies. In the scope of rail or intermodal and multimodal transportation, determining the capacity of freight terminals for normal conditions or designating certain backup terminals and determining their backup capacities for disrupted conditions could be other research avenues for the researchers.

3.4. Modeling and solution techniques

Table 11 provides an overview of the basic modeling/solution techniques developed in the HR literature. The modeling techniques are classified into simple formulations (i.e., link-based and route-based formulations) and multi-player game formulations. Solution techniques are also categorized into exact, heuristic, metaheuristic, and hybrid techniques. Exact methods solve the mod-

Table 9
Classification of articles studying HR problems based on their parameters.

Reference	Main input parameters and their types												
	Link's travel cost				Network demand	Link population loss	Node population loss	Weather condition	Link traffic flows	Rate of incidents	Accident severity	Incident probability	
	Economic cost ($)	Travel time	Length	General								Known	Unknown
Glickman (1983)	–	–	–	–	DE	DE	–	–	–	DE	DE	DE	–
Abkowitz and Cheng (1988)	DE	–	–	–	DE	DE	–	–	–	DE	DE	PR	–
Batta and Chiu (1988)	–	–	DE	–	DE	DE	DE	–	–	DE	DE	DE	–
Gopalan et al. (1990)	–	–	–	–	DE	DE	–	–	–	–	–	DE	–
Klein (1991)	–	–	DE	–	DE	PO	–	–	–	PO	–	–	–
Lindner-Dutton et al. (1991)	–	–	–	–	DE	DE	–	–	–	–	–	DE	–
Wijeratne et al. (1993)	DE	PR	DE	–	DE	–	–	–	–	–	–	PR	–
Beroggi (1994)	DE	–	–	–	DE	DE	–	RT	–	RT	–	DE	–
Patel and Horowitz (1994)	–	DE	DE	–	DE	DE	DE	DE	–	DE	–	DE	–
Beroggi and Wallace (1995)	DE	–	–	–	DE	DE	–	RT	–	DE	–	–	–
Karkazis and Boffey (1995)	–	–	–	–	DE	DE	–	–	–	DE	–	PR	–
Jin et al. (1996)	–	–	–	–	DE	DE	–	–	–	DE	–	DE	–
Jin and Batta (1997)	–	–	–	–	DE	DE	–	–	–	DE	–	DE	–
Nembhard and White Iii (1997)	–	–	DE	–	DE	DE	–	–	–	–	–	DE	–
Sherali et al. (1997)	–	–	–	–	DE	DE	–	–	–	–	–	DE	–
Verter and Erkut (1997)	DE	–	–	–	DE	DE	–	–	–	DE	–	DE	–
Marianov (1998)	–	–	–	DE	DE	DE	–	–	–	DE	–	DE	–
Iakovou et al. (1999)	DE	–	DE	–	DE	–	–	–	–	DE	–	–	–
Nembhard and White Iii (1999)	–	–	DE	–	DE	DE	–	–	–	–	–	DE	–
Erkut and Ingolfsson (2000)	–	–	–	–	DE	DE	–	–	–	PR	–	DE	–
Frank et al. (2000)	–	DY	DE	–	DE	DY	–	–	–	–	–	DY	–
Dell'Olmo et al. (2005)	–	–	DE	–	–	–	–	–	DE	–	–	–	–
Serafini (2006)	–	–	DE	–	DE	–	–	–	–	–	–	DE	–
Carotenuto et al. (2007a)	–	–	–	–	DE	DE	–	–	–	–	–	DE	–
Glickman et al. (2007)	–	–	DE	–	DE	DE	–	–	–	–	–	DE	–
Dadkar et al. (2008)	–	ST, DY	–	–	DE	ST, DY	–	–	–	ST, DY	–	ST, DY	–
Martí et al. (2009)	–	–	DE	–	DE	–	–	–	–	–	–	–	–
Verma (2009)	DE	–	–	–	DE	DE	–	–	–	DE	–	DE	–
Verma and Verter (2010)	–	–	–	DE	DE	DE	–	DE	–	–	–	–	–
Lozano et al. (2011)	–	DE	DE	–	DE	DE	–	–	DE	–	–	–	–
Verma et al. (2011)	DE	–	–	–	DE	DE	–	–	–	–	–	–	–
Verma et al. (2012)	DE	–	–	–	DE	DE	–	DE	–	–	–	–	–
Hamdi-Dhaoui et al. (2014)	DE	–	–	–	DE	–	–	–	–	–	–	–	–

(continued on next page)

Table 9 (*continued*)

Reference	Main input parameters and their types												
	Link's travel cost				Network demand	Link population loss	Node population loss	Weather condition	Link traffic flows	Rate of incidents	Accident severity	Incident probability	
	Economic cost ($)	Travel time	Length	General								Known	Unknown
Kang et al. (2014a)	–	–	–	–	DE	DE	–	–	–	–	–	DE	–
Kang et al. (2014b)	–	–	–	–	DE	DE	–	–	–	–	–	DE	–
Assadipour et al. (2015)	DE	–	–	–	DE	DE	–	–	–	–	–	–	–
Bronfman et al. (2015)	DE	–	DE	–	DE	–	DE	–	–	–	–	–	–
Fan et al. (2015)	–	DE	DE	–	DE	DE	–	–	–	DE	–	DE	–
Bronfman et al. (2016)	–	DE	–	–	DE	–	DE	–	–	–	–	–	–
Kheirkhah et al. (2016b)	DE	–	–	–	DE	–	–	–	–	–	–	–	–
Teoh et al. (2016)	–	–	DE	–	DE	DE	–	–	–	–	–	DE	–
Toumazis and Kwon (2016)	–	–	–	–	DE	ST	–	–	–	–	–	ST	–
Zhao and Zhu (2016)	DE	–	–	–	DE	DE	–	–	–	–	–	–	–
Garrido and Bronfman (2017)	–	–	–	–	DE	DE	–	–	–	–	–	DE	–
Hosseini and Verma (2017)	–	–	–	–	DE	DE	DE	–	–	DE	–	DE	–
Hosseini and Verma (2018)	–	–	–	–	DE	DE	DE	–	–	DE	–	DE	–
Kumar et al. (2018)	DE	–	–	–	DE	DE	–	–	–	–	–	DE	–
Wang et al. (2018)	DE	DE	DE	–	DE	DE	–	–	–	–	–	DE	–
Zhang et al. (2018)	DE	–	–	–	DE	DE	–	–	–	–	–	DE	–
Timajchi et al. (2019)	DE	–	DE	–	DE	–	–	–	–	–	DE	DE	–
Ke (2020)	DE	DE	–	–	DE	–	–	–	–	ST	–	ST	–
Hosseini and Verma (2021)	–	–	–	–	DE	DE	DE	–	–	DE	–	DE	–

***Technical comments*:** Glickman (1983) studied rail track conditions as a parameter. The costs related to vehicle damage, cargo damage, cleanup, and evacuation were studied by Abkowitz and Cheng (1988). Patel and Horowitz (1994) studied the incident probability for both network links and nodes. The weather condition has been considered as a function of the weather speed and direction (Karkazis & Boffey, 1995; Verma & Verter, 2010; Verma et al., 2012). Jin and Batta (1997) considered that the parameters of the model change once an accident occurs in the network. Verter and Erkut (1997) considered the carrier's driving records as an insurance-related parameter. In Iakovou et al. (1999), each vessel has a specific transportation cost depending on its tanker capacity (deadweight or DWT). The HR model proposed by Lozano et al. (2011) considers two scenarios for routing day and night that each one has its specific parameters. The economic costs are usually the summation of inbound and outbound drayage costs, rail haul cost, fixed cost to operate different types of intermodal train services, inventory holding cost, shortage cost and transshipment (pickup) cost, and the equipment acquisition cost at the terminals (Assadipour et al., 2015; Timajchi et al., 2019). Bronfman et al. (2015), 2016) assumed that the population is mostly located in vulnerable centers rather than around the network links. The rate of vehicles' emission (g/km) and vehicle's fixed cost are two specific parameters investigated by Teoh et al. (2016) and Zhao and Zhu (2016), respectively. Kumar et al. (2018) studied a set of other parameters including monetary loss due to truck stoppages, purchase finance loan (lease) cost of trucks, and cost of recovery.

Table 10
Classification of articles studying HR problems based on their decisions.

Reference	Congestion decision		Vehicle decision		Comments
	With queue discipline	Without queue discipline	Fleet assignment	Fleet planning	
Abkowitz and Cheng (1988)	–	–	√	–	-
Beroggi (1994)	–	√	–	–	-
Frank et al. (2000)	–	√	–	–	Parking decision on intermediate nodes
Verma et al. (2011)	–	–	–	√	Determining the number and makeup of each type of train services
Assadipour et al. (2015)	√	–	–	–	–
Teoh et al. (2016)	–	–	√	–	–
Toumazis and Kwon (2016)	–	–	√	–	–
Zhao and Zhu (2016)	–	–	√	√	Determining the number of vehicles needed to collect the wastes
Hosseini and Verma (2017)	–	–	√	–	–
Kumar et al. (2018)	–	–	√	√	–
Wang et al. (2018)	–	√	–	–	Waiting at vertices to prevent vehicles from moving in the echelon
Hosseini and Verma (2018)	–	–	√	–	–
Timajchi et al. (2019)	–	–	√	–	–
Ke (2020)	–	–	√	√	The capacity of terminals, number of needed trains and containers
Hosseini and Verma (2021)	–	–	√	–	–

Table 11
Classification of articles studying HR problems based on their modeling/solution techniques.

Property		References
Basic modeling techniques	Link-based formulation	Gopalan et al. (1990), Beroggi (1994), Sherali et al. (1997), Marianov (1998), Kang et al. (2014b), Bronfman et al. (2015), Fan et al. (2015), Bronfman et al. (2016), Teoh et al. (2016), Zhao and Zhu (2016), Garrido and Bronfman (2017), Hosseini and Verma (2017), Hosseini and Verma (2018), Kumar et al. (2018), Timajchi et al. (2019), Wang et al. (2018), Zhang ey al., (2018), Hosseini and Verma (2021)
	Route-based formulation	Glickman (1983), Abkowitz and Cheng (1988), Batta and Chiu (1988), Klein (1991), Lindner-Dutton et al. (1991), Wijeratne et al. (1993), Patel and Horowitz (1994), Beroggi and Wallace (1995), Karkazis and Boffey (1995), Jin et al. (1996), Jin and Batta (1997), Nembhard and White Iii (1997), Verter and Erkut (1997), Iakovou et al. (1999), Nembhard and White Iii (1999), Erkut and Ingolfsson (2000), Frank et al. (2000), Dell'Olmo et al. (2005), Serafini (2006), Carotenuto et al. (2007a), Glickman et al.(2007), Dadkar et al. (2008), Martí et al. (2009), Verma (2009), Verma and Verter (2010), Lozano et al. (2011), Verma et al. (2011), Verma et al. (2012), Hamdi-Dhaoui et al. (2014), Kang et al. (2014a), Assadipour et al. (2015), Kheirkhah et al. (2016b), Toumazis and Kwon (2016)
	Multi-player game (Demon approach)	Nash game: - Stackelberg game: Kheirkhah et al. (2016b)
Solution techniques	Exact	Sherali et al. (1997), Marianov (1998), Kang et al. (2014b), Zhao and Zhu (2016), Garrido and Bronfman (2017), Wang et al. (2018), Glickman (1983), Abkowitz and Cheng (1988), Abkowitz and Cheng (1988), Wijeratne et al. (1993), Patel and Horowitz (1994), Beroggi and Wallace (1995), Karkazis and Boffey (1995), Jin et al. (1996), Jin and Batta (1997), Nembhard and White Iii (1997), Verter and Erkut (1997), Erkut and Ingolfsson (2000), Dell'Olmo et al. (2005), Serafini (2006), Glickman et al.(2007), Verma (2009), Lozano et al. (2011), Kang et al. (2014a), Kheirkhah et al. (2016b)
	Heuristic	Gopalan et al. (1990), Bronfman et al.(2015), Fan et al. (2015), Bronfman et al.(2016), Hosseini and Verma (2017), Hosseini and Verma (2018), Zhang ey al., (2018), Lindner-Dutton et al. (1991), Iakovou et al. (1999), Nembhard and White Iii (1999), Frank et al. (2000), Carotenuto et al. (2007a), Dadkar et al. (2008), Verma and Verter (2010), Assadipour et al. (2015), Toumazis and Kwon (2016), Hosseini and Verma (2021)
	Metaheuristic	Genetic algorithm: Dadkar et al. (2008), Kumar et al. (2018) Tabu Search: Verma et al. (2012) A new GRASP procedure: Martí et al. (2009) NSGA-II: Hamdi-Dhaoui et al. (2014) Multi-objective differential evolution (MODE): Teoh et al. (2016)
	Hybrid	Hybrid dynamic programming method: Klein (1991) Memetic algorithm: Verma et al. (2011) Hybrid Genetic algorithm: Timajchi et al. (2019)

Technical comments: A Lagrangian dual approach with a gap-closing procedure was applied as a heuristic method in Gopalan et al. (1990). An exact branch-and-bound technique was implemented by Karkazis and Boffey (1995), Sherali et al. (1997), and Kang et al. (2014a). Assadipour et al. (2015) proposed a solution algorithm based on the combination of genetic algorithm and Cplex solver as hybridization between metaheuristic and exact algorithms. The exact solution algorithm proposed by Dell'Olmo et al. (2005) was based on an iterative penalty method. Two different heuristic algorithms, named BU* and DU*, were proposed by Nembhard and White Iii (1999). A dynamic programming solution technique and the Lagrangian relaxation technique were implemented by Nembhard and White Iii (1997) and Jin et al. (1996), respectively. Frank et al. (2000) proposed two heuristic solution approaches named weight-guided solution method and intermediate nodes solution method to solve larger instances of the HR problem. Carotenuto et al. (2007a) proposed two heuristic solution methods named greedy (GD) and randomized greedy (RGD) methods together with a Lagrangian relaxation-based lower bound to solve larger instances of the HR problem. In the study of Dadkar et al. (2008), a heuristic solution approach was proposed for solving the HR problem as a K-shortest path problem. GA is applied to find a set of optimal routes from the resulted k-shortest paths.

els to optimality (i.e., guarantee the optimality of the final solution); however, they are only able to solve small-sized instances of the problems and they take too much time to be executed. On the other hand, heuristic and metaheuristic techniques are approximation algorithms that do not guarantee optimality but they can find (near-) optimal solutions in a reasonable execution time.

As is can be seen in Table 11, link- and route-based formulations are the most common technique for modeling HR problems, while multi-player game formulations have not been used except in a single study by Kheirkhah et al. (2016b), in which the authors established the demon approach by proposing a bi-level model as a Stackelberg game with the leader as the demon and the follower as the carriers. Developing more multi-player game formulations, particularly as Nash games, could be investigated in HR problems as a future research direction. In a Nash game, the equilibrium solution can be considered as the compromise solution for all players of the game.

Among exact methods, Benders decomposition has been mostly used to solve HR problems. It is worth mentioning that the contribution of metaheuristic algorithms for solving large-sized HR problems is weak and needs to be strengthened in the future. Indeed, the majority of studies have used either exact or heuristic algorithms to solve HR problems while these techniques are not able to solve real-world large instances due a high computational effort that might be needed. Among different metaheuristic algorithms, genetic algorithms (Dadkar et al., 2008; Kumar, Roy, Verter & Sharma, 2018), tabu search (Verma, Verter & Zufferey, 2012), GRASP (Martí et al., 2009), non-dominated sorting genetic algorithm-II (NSGA-II) (Hamdi-Dhaoui et al., 2014; Karimi-Mamaghan et al., 2020a, a, 2021b), and multi-objective differential evolution (MODE) (Teoh et al., 2016) are the only metaheuristic algorithms applied in the literature. Therefore, implementing other metaheuristic algorithms, such as particle swarm optimization (PSO), adaptive large neighborhood search (ALNS), etc., can be an important future research direction to improve the speed and accuracy of the existing solution techniques for HR problems.

3.5. Case studies

The details of the investigated case studies for HR problems are tabulated in Table 12, wherein we show which paper has used real and/or hypothetical (randomly generated) case studies of which country and what has been the size of the case studies in terms of the number of nodes, links, routes, and customers in the network. Some papers either have not used a real case study or they have not mentioned (NM) detailed information on their case study. Furthermore, the largest hypothetical case belongs to the study of Sherali, Brizendine, Glickman and Subramanian (1997) with 3281 and 5466 nodes and links, respectively. Table 12 shows that the case studies mostly belong to the USA, Italy, Chile, China, India, and Spain. Accordingly, we encourage researchers to study HR problems for the case studies that belong to other countries.

4. Classification of hrs problems

In the context of HRS problems, scheduling means distributing hazmat shipments based on different time intervals of a given time horizon to meet the objectives (Bell, 2006). The output of this problem is the optimal route and the optimal departure time for each demand (Nozick, List & Turnquist, 1997). It is obvious that the HRS problem is an extension of the HR problem with the possibility of scheduling the hazmat shipments; thus, all the explanations presented for HR problems remain valid for HRS problems. As a more advanced version, the HRS problem has some other specific characteristics/features due to taking the scheduling properties into account in an HR problem, such as considering multiple periods and a dynamic demand in the network.

4.1. Assumptions

Similar to the HR problem, this section characterizes the studies on the HRS problem based on their assumptions in Table 13.

From Table 13, it can be seen that no study has been devoted to HRS problems considering the airway mode and or multimodal transportation and even the contribution of rail and maritime modes of transportation is low; thus, they are worthy of investigation in HRS problems as future research directions. Nearly a half of the literature (47%) has integrated scheduling into global routing problems, where the transportation mode has been either road (93%) or rail (7%). In addition, about 27% of the literature, which mostly includes articles before 2007, has studied local routing in HRS problems with road mode of transportation. Regarding the number of depots in hazmat vehicle routing problems, the single-depot structure has gained popularity since 2008 and has usually been applied to the road mode of transportation (75%) or maritime transportation (25%). On the other hand, no paper was found in the literature studying hazmat vehicle routing problems with multiple depots.

Similar to the assumptions in HR problems, the carriers are again the major players in HRS problems, but no study has investigated the competition/collaboration among the carriers. In terms of the type of vehicles, nearly 67% of the papers have considered a homogenous fleet while 33% of the literature, mostly the papers published after 2008, have assumed a heterogeneous fleet. This trend, assuming a heterogeneous fleet, was also observed in the HR problem.

Nearly 73% of the literature, particularly the literature after 2013, has addressed multi-period HRS problems, while certain studies (Zografos & Androutsopoulos, 2004, 2008; Carotenuto et al., 2007b; Ma et al., 2012) have treated the problem by tracking time within a single scheduling horizon. The main reason goes back to the simplicity of single-period HRS problems compared to multi-period ones.

As it was mentioned in Section 3.1, the increase in the volume and type of hazmat shipments has obliged carriers to move multiple classes of hazmat (Siddiqui & Verma, 2015; Szeto, Farahani & Sumalee, 2017; Mohri, Asgari, Farahani, Bourlakis & Laker, 2020). As the statistics show, the application of multiple hazmat classes in HRS is more common than in HR. The reason is that in HRS, contrary to HR, the possibility of exploring the simultaneous existence of two hazmat vehicles on the same link and at the same time is possible.

4.2. Objectives and constraints

Tables 14 and 15 classify, respectively, the main objectives and constraints studied in the HRS literature and also provide useful and practical hints on some papers at the end of the tables as technical comments.

Similar to HR problems, the contributions of the risk (100%) and economic (53%) objectives in HRS problems are significantly larger than for other objectives. Although three papers (Carotenuto et al., 2007b; Ma et al., 2012; Fang et al., 2017) have studied equity issues in HRS through equity constraints (i.e., risk on each link, edge capacity restriction, and the distance between hazmat vehicles), equity and environmental objectives have not been still investigated in HRS problems. The reason mainly goes back to the lower priority of these objectives from the carriers' viewpoint.

As can be seen, the papers minimizing the expected risk as the objective function constitute a major part (up to 53%) of the HRS literature, while the HRS literature is deprived of studies considering other risk measures like VaR, conditional probability, maximum risk, mean-variance, and disutility function. This absence could be dealt with in future research studies. In contrast to the HR literature, in which about 90% of papers address economic concerns through minimizing monetary transportation costs, nearly 67% of the HRS literature has considered economic objectives by minimizing the total travel time. The reason could be the availability of the links travel times in HRS problems because they address scheduling issues. Hence, there is no longer the need to convert time to monetary costs.

Table 12
Classification of articles studying HR problems based on their case studies.

Reference	Real cases					Hypothetical case					Data source		
	City/Country	Size				#Cases	Size				Real-life case	Random	Web reference
		#Nodes	#Links	#Routes	#Customers		#Nodes	#Links	#Routes	#Customers			
lickman (1983)	Class I railroad the USA	–	–	40	–	–	–	–	40	–	√	–	–
Abkowitz and Cheng (1988)	New York [*a]	NM*	NM	–	–	–	–	–	–	–	√	√	–
Batta and Chiu (1988)	–	–	–	–	–	–	–	–	–	–	–	–	–
Gopalan et al. (1990)	New York [*a]	50	NM	–	–	–	–	–	–	–	√	√	–
Klein (1991)	–	–	–	–	–	–	9	16	–	–	–	√	–
Lindner-Dutton et al. (1991)	New York [*a]	–	–	20	–	–	–	–	4	–	√	√	–
Wijeratne et al. (1993)	New York [*a]	46	–	10	–	–	–	–	–	–	√	√	–
Beroggi (1994)	–	–	–	–	–	–	–	–	–	–	–	–	–
Patel and Horowitz (1994)	Sioux Falls.	423	517	–	–	–	–	–	–	–	√	√	–
Beroggi and Wallace (1995)	Switzerland	NM	–	–	–	–	–	–	–	–	√	√	–
Karkazis and Boffey (1995)	–	–	–	–	–	5	7	36	–	–	–	√	–
Jin et al. (1996)	Albany city of New York	50	NM	–	–	–	–	–	–	–	√	√	–
Jin and Batta (1997)	Albany city of New York	50	NM	–	–	–	–	–	–	–	√	√	–
Nembhard and White Iii (1997)	Cleveland city of Ohio	131	202	–	–	–	–	–	–	–	√	√	–
Sherali et al. (1997)	Bethlehem city of Pennsylvania	12	15	–	–	11	3281	5466	–	–	√	–	√
Verter and Erkut (1997)	from Detroit to Houston	–	–	2	–	–	–	–	–	–	–	√	–
Marianov (1998)	–	–	–	–	–	–	28	45	–	–	–	√	–
Iakovou et al. (1999)	Gulf of Mexico.	58	NM	–	–	–	11	18	–	–	√	–	√
Nembhard and White Iii (1999)	Cleveland city of Ohio	131	202	–	–	–	–	–	–	–	√	√	–
Erkut and Ingolfsson (2000)	Allentown to Wichita, Iowa state [*b]	NM	NM	–	–	–	–	–	–	–	√	√	–
Frank et al. (2000)	U.S. highways	57,000	NM	–	–	–	–	–	–	–	√	–	√
Dell'Olmo et al. (2005)	Rome	699	1754	–	–	2	200	370	–	–	√	–	–
Serafini (2006)	–	–	–	–	–	–	4	4	–	–	–	√	–
Carotenuto et al. (2007a)	Lazio region containing Rome	311	441	–	–	–	–	–	–	–	√	–	–
Glickman et al. (2007)	Class I railroad the USA	–	–	24	–	–	–	–	–	–	–	√	–
Dadkar et al. (2008)	Mississippi and Florida	1173	1403	–	–	9	153	179	–	–	√	√	–

(*continued on next page*)

Table 12 (*continued*)

Reference	Real cases					Hypothetical case					Data source		
	City/Country	Size				#Cases	Size				Real-life case	Random	Web reference
		#Nodes	#Links	#Routes	#Customers		#Nodes	#Links	#Routes	#Customers			
Martí et al. (2009)	Spain	NM	NM	–	–	10	500	–	–	–	–	√	√
Verma (2009)	the southeast US	34	NM	–	–	–	–	–	–	–	√	√	–
Verma and Verter (2010)	Eastern US (rail and road)	604	–	600	–	–	–	–	210	–	√	√	√
Lozano et al. (2011)	Mexico City	NM	NM	–	–	–	–	–	–	–	√	–	√
Verma et al. (2011)	Midwestern United States	25	NM	–	–	–	–	–	–	–	–	√	√
Verma et al. (2012)	Norfolk Southern in the US	20	NM	–	–	–	–	–	–	–	√	√	–
Hamdi-Dhaoui et al. (2014)	–	–	–	–	–	800	–	–	–	35	–	√	–
Kang et al. (2014a)	Albany city of New York	90	108	–	–	5	–	–	30	–	√	–	√
Kang et al. (2014b)	Albany city of New York	60	148	–	–	1	9	12	–	–	√	–	√
Assadipour et al. (2015)	Norfolk Southern in the US	20	NM	–	–	–	–	–	–	–	√	√	–
Bronfman et al. (2015)	Santiago city of Chile (2 cases)	2212	6681	–	–	–	–	–	–	–	√	–	–
Fan et al. (2015)	Shanghai city of China	8914	27,625	–	–	1	6	9	–	–	√	√	√
Bronfman et al. (2016)	Santiago city of Chile	2212	6681	–	–	–	–	–	–	–	√	–	–
Kheirkhah et al. (2016b)	–	–	–	–	–	7	–	–	–	35	–	√	–
Teoh et al. (2016)	–	–	–	–	–	74	–	–	–	–	–	√	–
Toumazis and Kwon (2016)	Buffalo	90	149	–	–	–	–	–	–	–	√	–	√
Zhao and Zhu (2016)	Nanchuan city of China	54	–	–	–	100	100	–	–	–	√	√	–
Garrido and Bronfman (2017)	Santiago city of Chile	2030	5790	–	–	–	6	8	–	–	–	√	√
Hosseini and Verma (2017)	Class I railroad the USA	25	–	–	–	–	–	–	–	–	√	√	–
Hosseini and Verma (2018)	Class I railroad the USA	25	–	–	–	–	–	–	–	–	√	√	–
Kumar et al. (2018)	Ahmedabad, Gujarat, India	16	44	–	–	–	5	6	–	–	√	√	√
Wang et al. (2018)	–	–	–	–	–	10	–	–	–	8	–	√	–
Zhang et al. (2018)	–	–	–	–	–	12	–	–	–	75	–	√	–
Timajchi et al. (2019)	–	–	–	–	–	15	–	–	–	50	–	√	–
Hosseini and Verma (2018),	Class I railroad the USA	25	–	–	–	–	–	–	–	–	√	√	–

*NM: not mentioned; a: only Albany, Schenectady, and Troy cities of New York; b: two cases were used; (1): Allentown to Wichita (2): Iowa State.

Table 13
Classification of articles studying HRS problems based on their assumptions.

Reference	Main assumptions											
	Transportation mode	Problem structure				Model players		Players competition type	Vehicle type		Single/multiple periods	Single/multiple hazmat classes
		Local routing	Global routing	Vehicle routing		Carrier	Others		Homogenous	Heterogeneous		
				Single depot	Multiple depots							
Nozick et al. (1997)	Road	*	–	–	–	*	–	–	*	–	M	S
Zografos and Androutsopoulos (2004)	Road	–	–	*	–	*	–	–	–	*	S	S
Chang et al. (2005)	Road	*	–	–	–	*	–	–	*	–	M	S
Akgün, Parekh, Batta and Rump (2007)	Road	–	*	–	–	*	–	–	*	–	M	S
Carotenuto et al. (2007b)	Road	–	*	–	–	*	–	–	*	–	S	S
Erkut and Alp (2007a)	Road	*	–	–	–	*	–	–	*	–	M	S
Zografos and Androutsopoulos (2008)	Road	–	–	*	–	*	ER[a]	–	–	*	S	M
Androutsopoulos and Zografos (2010)	Road	–	*	*	–	*	–	–	*	–	M	S
Ma et al. (2012)	Road	–	–	*	–	*	–	–	*	–	S	S
Toumazis and Kwon (2013)	Road	*	–	–	–	*	–	–	*	–	M	S
Faghih-Roohi, Ong, Asian and Zhang (2016)	Maritime	–	–	*	–	*	–	–	–	*	M	S
Siddiqui and Verma (2015)	Road	–	*	–	–	*	–	–	*	–	M	M
Fang et al. (2017)	Rail	–	*	–	–	*	–	–	–	*	M	S
Szeto et al. (2017)	Road	–	*	–	–	*	–	–	*	–	M	M
Mohri et al. (2020)	Road	–	*	–	–	*	–	–	–	*	M	M
Statistics (%)	Road: 86 Rail: 7 MI: 0 Maritime: 7	27	47	27	0	100	7	0	67	33	S: 27 M: 73	S: 73 M: 27

a: ER stands for Emergency responder

Table 14
Classification of articles studying HRS problems based on their objectives.

Main objectives		Objectives: SOP or MOP
Risk (Min)	Expected risk	SOP: Akgün et al. (2007), Erkut and Alp (2007a), Szeto et al. (2017) MOP: Zografos and Androutsopoulos (2004), Chang et al. (2005), Zografos and Androutsopoulos (2008), Siddiqui and Verma (2015), Mohri et al. (2020)
	Population exposure	MOP: Nozick et al. (1997), Chang et al. (2005)
	Incident probability	MOP: Chang et al. (2005)
	Perceived risk	MOP: Androutsopoulos and Zografos (2010)
	Conditional value-at-risk (CVaR)	SOP: Toumazis and Kwon (2013), Faghih-Roohi et al. (2016)
	General	MOP: Nozick et al. (1997), Carotenuto et al. (2007b)
Economic (Min)	Total Monetary costs ($)	MOP: Ma et al. (2012), Siddiqui and Verma (2015)
	Total travel time	MOP: Zografos and Androutsopoulos (2004), Chang et al. (2005), Zografos and Androutsopoulos (2008), Androutsopoulos and Zografos (2010), Ma et al. (2012), Mohri et al. (2020)
	Total route length	MOP: Nozick et al. (1997)
	Total general cost	MOP: Fang et al. (2017)
	Total shipment delay	MOP: Carotenuto et al. (2007b)

Technical comments: Nozick et al. (1997) minimized the rate of accidents as a risk-related objective beside the total route length as the economic objective. Chang et al. (2005) proposed a general multi-objective HRS problem depending on the size of the problem instances. For small-sized instances, the objectives are to minimize the total travel time, accident probability, and population exposure, and for big-sized instances, the objectives are to minimize the total travel time and expected risk. The proposed HRS model by Carotenuto et al. (2007b) has two phases, wherein the first phase, risk objective is minimized to identify a set of low-risk routes and in the second phase, the total shipment delay is minimized. The model proposed by Ma et al. (2012) minimizes the number of utilized vehicles in the HRS as a representative measure of the total fixed cost of vehicles. Fang et al. (2017) minimized the weighted sum of earliness and tardiness for each demand and the holding cost at each yard. In this regard, the authors incorporated penalty costs for earliness, tardiness, and holding time to model the objective function.

Table 15
Classification of articles studying HRS problems based on their constraints.

Main constraints		References
Equity	Risk on each link	Fang et al. (2017)
	Edge capacity restriction	Ma et al. (2012)
	The distance between hazmat vehicles	Carotenuto et al. (2007b)
Number of available vehicles		Zografos and Androutsopoulos (2004), Faghih-Roohi et al. (2016), Mohri et al. (2020)
Time-window constraints		Zografos and Androutsopoulos (2004), Chang et al. (2005), Carotenuto et al. (2007b), Zografos and Androutsopoulos (2008), Androutsopoulos and Zografos (2010), Ma et al. (2012), Siddiqui and Verma (2015), Fang et al. (2017)
Inaccessible roads		Szeto et al. (2017)
Vehicles capacity		Fang et al. (2017), Mohri et al. (2020)
Limiting route duration		Erkut and Alp (2007a)
FIFO constraints		Toumazis and Kwon (2013), Mohri et al. (2020)
Maximum number of allowable trips during a planning horizon		Siddiqui and Verma (2015)

Technical comments: Fang et al. (2017) investigated an HRS problem under rail mode of transportation, in which each train has a capacity of moving several rail cars.

An overall view on the constraints in HRS problems (Table 15) shows that most of them are concerned about time. For example, time window constraints, with a 53% contribution, usually aim at restricting early or late hazmat dispatching or delivering. Limiting route duration and First-In-First-Out (FIFO) dispatching constraints are the other time-related constraints. The FIFO dispatching constraints in an HRS problem with waiting time on routes can also provide equity between hazmat vehicles (Mohri et al., 2020).

The literature of HRS does not investigate other important constraints, particularly the risk-related constraints such as excluding undesirable routes, limiting total consequence/risk in the network, limiting risk/accident probability/consequence/capacity/length of the routes, and shipment suspension. Only three papers (Erkut & Alp, 2007a; Szeto et al., 2017; Siddiqui & Verma, 2015) have partially addressed these constraints by making roads inaccessible, limiting route duration, and bounding the maximum number of allowable trips during a planning horizon. Indeed, each of these shortages in terms of objectives and constraints can be studied as future research.

4.3. Parameters and decisions

The type of parameters incorporated in HRS problems is presented in Table 16. As the table shows, the main parameters are link population loss (among 93% of the papers), link travel time (among 87% of the papers), network demand (among 87% of the papers), and known incident probability (among 73% of the papers). Chang, Nozick and Turnquist (2005) is the only paper that considers the link travel time, the link population loss, and incident probability as uncertain (probabilistic) parameters. Table 16 also reveals that the use of dynamic parameters in HRS problems is considerable. The reason is that modeling an HRS problem through multiple periods allows researchers to simply consider different values for parameters in different periods (i.e., dynamic parameters), even if in each period the parameters are deterministic with no uncertainty. Notably, Table 16 highlights that the demand of hazmat has been modeled neither as a dynamic parameter nor as an uncertain one; however, in real-world settings, demand is the main parameter that is uncertain. Accordingly, the main research gaps in this regard can be expressed as (i) the lack of uncertain parameters in HRS, (ii) the absence of studies in the literature considering the links' economic cost and network demand under uncertainty (e.g., probabilistic, stochastic, dynamic, etc.), and (iii) the fact that the study of Fang et al. (2017) is the only paper that considers vehicle speed in the modeling of the HRS problem, while other vehicle characteristics, such as load capacity and age of the vehicles, have not been yet investigated in the HRS literature.

Table 16
Classification of articles studying HRS problems based on their parameters.

Reference	Main input parameters and their types [a]										
	Link's travel cost				Network demand	Link population loss	Weather condition	Links traffic flows	Rate of incidents	Incident probability	
	Economic costs ($)	Travel time	Length	general						Known	Unknown
Nozick et al. (1997)	–	–	DE	–	DE	DY	–	–	DY	DY	–
Zografos and Androutsopoulos (2004)	–	DE	–	–	DE	DE	–	–	–	DE	–
Chang et al. (2005)	–	PR, DY	–	–	DE	PR, DY	–	–	PR, DY	PR, DY	–
Akgün et al. (2007)	–	DY	–	–	DE	DE	DY	–	DE	DY	–
Carotenuto et al. (2007b)	–	DE	–	–	DE	DE	–	–	–	DE	–
Erkut and Alp (2007a)	–	DY	–	–	DE	DY	–	–	–	DY	–
Zografos and Androutsopoulos (2008)	–	DE	–	–	DE	DE	–	–	DE	DE	–
Androutsopoulos and Zografos (2010)	–	DY	–	–	DE	DY	–	–	–	DY	–
Ma et al. (2012)	–	DE	–	–	DE	–	–	–	–	–	–
Toumazis and Kwon (2013)	–	DY	–	–	DE	DY	–	DY	–	DY	–
Siddiqui and Verma (2015)	DE	DE	–	–	DE	DE	–	–	–	DE	–
Faghih-Roohi et al. (2016)	–	DY	–	–	–	DY	–	–	–	DY	–
Fang et al. (2017)	–	DE	DE	–	–	DE	–	–	–	–	–
Szeto et al. (2017)	–	–	–	–	DE	DE	–	–	–	–	DE
Mohri et al. (2020)	DE	DE	–	–	DE	DE	–	–	–	–	DE

Technical comments: Zografos and Androutsopoulos (2004) assumed the service time in the network nodes as a deterministic parameter. In Akgün et al. (2007), the travel speed and accident rate is changing over time due to the weather conditions, and the incident probability is calculated for both links and nodes, before entering and after departing from the links or nodes. The earliest departure time and the shortest distance between any two hazmat vehicles are other parameters defined by Carotenuto et al. (2007b). Fixed vehicle cost is a parameter considered by Ma et al. (2012). In Fang et al. (2017), the risk of each link depends on the speed of trains on the link. In the proposed maritime HRS model by Siddiqui and Verma (2015), the incident consequence is a function of cleanup cost, environmental damages, and indemnification charges, and the total transportation cost is a function of vessels' travel cost and waiting cost (in ports).

Table 17
Classification of articles studying HRS problems based on their decisions.

Reference	Congestion decision	Vehicle decision		Details
	With queue discipline	Fleet assignment	Fleet planning	
Zografos and Androutsopoulos (2004)	–	*	–	–
Akgün et al. (2007)	–	–	–	Parking decision
Erkut and Alp (2007a)	–	–	–	–
Zografos and Androutsopoulos (2008)	–	*	–	
Androutsopoulos and Zografos (2010)	–	–	–	–
Siddiqui and Verma (2015)	–	–	–	Waiting is possible in the depot
Faghih-Roohi et al. (2016)	–	*	–	–
Fang et al. (2017)	–	*	–	–
Szeto et al. (2017)	–	–	–	–
Mohri et al. (2020)	*	*	–	Waiting is possible

Table 18
Classification of articles studying HRS problems based on their modeling/solution techniques.

Attribute		References
Basic modeling techniques	Demon approach	Nash game: Szeto et al. (2017), Stackelberg game: Mohri et al. (2020)
	Link-based formulation	Zografos and Androutsopoulos (2004), Erkut and Alp (2007a), Zografos and Androutsopoulos (2008), Ma et al. (2012), Szeto et al. (2017), Mohri et al. (2020)
	Route-based formulation	Nozick et al. (1997), Chang et al. (2005), Akgün et al. (2007), Carotenuto et al. (2007b), Androutsopoulos and Zografos (2010), Toumazis and Kwon (2013), Siddiqui and Verma (2015), Faghih-Roohi et al. (2016), Fang et al. (2017)
Solution techniques	Exact	Nozick et al. (1997), Akgün et al. (2007), Erkut and Alp (2007a), Androutsopoulos and Zografos (2010), Toumazis and Kwon (2013), Siddiqui and Verma (2015), Faghih-Roohi et al. (2016)
	Heuristic	Nozick et al. (1997), Zografos and Androutsopoulos (2004), Chang et al. (2005), Akgün et al. (2007), Zografos and Androutsopoulos (2008), Fang et al. (2017), Szeto et al. (2017)
	Metaheuristic	Tabu search: Carotenuto et al. (2007b), Ma et al. (2012), ALNS: Mohri et al. (2020)

Technical comments: Nozick et al. (1997) proposed an enhanced solution algorithm based on the multi-labeling shortest path to solve the HRS problem. The authors claimed that the proposed algorithm is unable to obtain optimal solutions for time-dependent problems. Akgün et al. (2007) developed four different heuristic algorithms to solve the HRS problem. Erkut and Alp (2007a) applied dynamic programming as an exact solution method to solve the HRS problem. In Ma et al. (2012), a tabu search algorithm was applied with an adaptive penalty mechanism (TSAP). Mohri et al. (2020) proposed a modified ALNS algorithm to solve the HRS problem.

The major decisions taken in the HRS literature, apart from routing and scheduling decisions, are presented in Table 17. To the best of our knowledge, Mohri et al. (2020) is the only paper that has investigated the waiting time of hazmat shipments in the HRS problem by considering a FIFO queue discipline in waiting nodes or links. Indeed, ignoring the waiting time of hazmat shipments in the intermediate nodes (transit yard) can significantly affect the scheduling results and subsequently the model's objectives. Therefore, it is highly recommended to appropriately investigate the waiting time of hazmat shipments in HRS problems (Mohammadi, Jula & Tavakkoli-Moghaddam, 2017). As another interesting future research direction, other decisions related to fleet planning such as purchasing or leasing vehicles is worthy of investigation. Furthermore, making decisions on the selection of transportation modes in a multimodal network and even consolidating/packing different classes of hazmat in vehicles, trains, vessels, or airplanes are also suggested to be studied as future works.

4.4. Modeling and solution techniques

Table 18 classifies the basic modeling and solution techniques implemented in the HRS literature and also shows that both link-based and route-based formulations have been remarkably applied to model HRS problems. Furthermore, multi-player game formulations have been used by only two research works, where carriers play a Nash game (Szeto et al., 2017) or a Stackelberg game (Mohri et al., 2020) with one or multi virtual demons. As a promising future direction, multi-player game formulations could can used when some independent hazmat carriers with different risk attitudes exist and the values of their objectives (e.g., risk and cost) depend on all the carriers' decisions and not only on their own decisions.

In terms of solution techniques, exact and heuristic solution algorithms have been the most popular solution techniques so far, and the only employed metaheuristic algorithms are Tabu Search and ALNS algorithms to solve HRS problems. Accordingly, the application of other metaheuristic algorithms such as evolutionary algorithms (e.g., genetic algorithm, differential evolution, etc.) for solving HRS problems can be an important research direction.

4.5. Case studies

Table 19 reviews practical information about case studies in the HRS literature. The majority of the case studies belong to some regions in the U.S., Italy, Greece, and Singapore. Hence, as for HR problems, it could be very interesting to study the HRS in other countries. The largest sizes of the real and hypothetical cases case studies are 5521 nodes and 6756 links, and 600 nodes and 551 links, respectively.

5. Classification of htnd problems

The transportation network design problem has a broad application in all available transportation modes. Inherently, this problem can be modeled as a Stackelberg game between a leader and a follower. The leader is usually a single planner (e.g., the government) or multiple planners with or without collaboration. The follower might be a set of users with or without collaboration. The leader peruses different objectives in economic, social, environmental, and political contexts by regulating different strategic, tactical, and operational rules, while the follower seeks to optimize its objectives following the regulations. In this regard, bi-level

Table 19
Classification of articles studying HRS problems based on their case studies.

Reference	Real cases					Hypothetical case					Data source		
	City/Country	Size				#Cases	Size				Real-life case	Random	Web reference
		#Nodes	#Links	#Routes	#Customers		#Nodes	#Links	#Routes	#Customers			
Nozick et al. (1997)	U.S. Northeastern state	–	–	–	–	–	–	–	–	–	*	*	–
Zografos and Androutsopoulos (2004)	–	–	–	–	–	6	–	–	–	100	–	*	–
Chang et al. (2005)	Portland, Wilmington,	247	1158	–	–	–	22	34	–	–	–	*	*
Akgün et al. (2007)	Texas	5521	6756	–	–	–	12	11	–	–	*	*	*
Carotenuto et al. (2007b)	Lazio region	311	441	–	–	–	–	–	–	–	*	–	–
Erkut and Alp (2007a)	U.S. Northeastern state [a]	138	368	–	–	–	–	–	–	–	*	*	–
Zografos and Androutsopoulos (2008)	Attica region in Greece	NM	NM	–	–		80	–	–	–	*	*	–
Androutsopoulos and Zografos (2010)	–	–	–	–	–	3	600	551	–	–	–	*	–
Ma et al. (2012)	–	–	–	–	–	56	–	–	–	100	–	*	–
Toumazis and Kwon (2013)	Buffalo	90	148	–	–	–	–	–	–	–	*	–	*
Siddiqui and Verma (2015)	Saudi Arabia to Europe and the US	–	–	2	–	–	–	–	–	–	*	–	*
Faghih-Roohi et al. (2016)	Singapore (major roads)	9	13	–	–	4	22	41	–	–	*	*	–
Fang et al. (2017)	Class I railroad the USA	25	82	–	–	–	–	–	–	–	*	*	–
Szeto et al. (2017)	Singapore	25	29	–	–	–	8	11	–	–	*	–	*
Mohri et al. (2020)	Singapore	25	29	–	–	140	67	152	–	–	*	–	*

a: Northeastern U.S. interstate highway network optimization is a common technique in modeling leader-follower (Stackelberg) games.

The HTND problem fits with this general description. The government, as the leader, seeks to optimize its economic, social, and environmental objectives through regulating different policies including link closure (i.e., for one or many OD pairs, hazmat classes, and time periods) (Kara and Verter, 2004, Erkut & Alp, 2007b; Erkut & Gzara, 2008, Esfandeh, Batta & Kwon, 2017), link capacity restriction (Bianco et al., 2009a), toll pricing (i.e., on links, nodes or certain hazmat classes) (Marcotte, Mercier, Savard & Verter, 2009; Bianco et al., 2015), lane reservation (Zhou et al., 2013), and signal setting (Chiou, 2016, 2017). Nevertheless, freight forwarders, in their role as the follower, optimize their costs, which are mainly made up of monetary routing and scheduling costs (i.e., delay costs).

5.1. Assumptions

The main assumptions considered in the HTND problem are tabulated in Table 20. Looking at Table 20 reveals that the majority of the papers (about 82%) have studied the HTND problem on the road network, and only a few papers have studied HTND for the railway system (Reilly, Nozick, Xu & Jones, 2012; Jabbarzadeh, Azad & Verma, 2020) or multimodal transportation (Assadipour, Ke & Verma, 2016; Fontaine et al., 2020). Accordingly, a first future research direction could be studying the HTND problem for the maritime, rail, or even multimodal transportation modes.

In terms of the structure of the HTND problem, the global routing problem has obtained the highest popularity with up to 92% of contributions, while only two papers have studied other structures, including local routing (Dadkar, Nozick & Jones, 2010) and vehicle routing with one depot (Kheirkhah et al., 2016b). Indeed, the local routing problem seems to have weak application in HTND problems because in most cities more than a single hazmat carrier is operating and the government regulates certain policies to include all of them. In addition, the number of contributions to hazmat vehicle routing problems is low. In this regard, the work of Kheirkhah et al. (2016a) is the single paper that has studied a network with a single depot and multiple customers; however, in urban areas, hazmat vehicles often make more than a single delivery on their routes. Furthermore, no paper has studied vehicle routing problems with multiple depots; however, in real settings, each carrier has its own depot. These gaps deserve to be addressed in future research.

The statistics of Table 20 also show that nearly 91% of the reviewed papers consider a homogenous fleet, where only Assadipour et al. (2016) and Jabbarzadeh et al. (2020) have considered a heterogeneous fleet in the HTND problem.

Esfandeh et al. (2017) was found as the single paper studying the HRS problem as a second-level problem for an HTND problem, wherein the hazmat shipments are transported over multiple periods. Starting from this work, one could consider incorporating the HRS problem as the second-level problem in the HTND's bi-level optimization structure for the rail and multimodal transportation modes as an interesting future research direction.

5.2. Objectives and constraints

The main objectives and constraints considered in HTND problems are presented in Tables 21 and 22, respectively. Due to the nature of the HTND problem to develop bi-level optimization models, it can be seen from Table 21 that the majority of the papers in the literature have studied MOP with different risk- and cost-related objectives. The most common risk-related objectives minimized either by the government or carriers are the expected risk and the population exposure. Hence, incorporating other risk measures like VaR, conditional probability, mean-variance, and disutility function in the HTND problem could be valuable contributions to the literature of the HTND problem. In addition, some important hints and useful information have been provided as technical comments at the end of Table 21.

As can be seen in Tables 21 and 22, the lack of environmental objectives/constraints is evident, while the government as the main player in this problem should seek the environmental objectives. Moreover, only two papers (Bianco et al., 2009, 2015) have considered the maximization of equity as an objective function in the HTND literature. Hence, it is recommended as future research directions to incorporate environmental and social concerns when studying HTND problems. For instance, certain introduced equity measures in Section 2.2 (e.g., dissimilarity and routes overlap) can be incorporated into HTND problems. In addition, considering new constraints for the HTND problem such as limiting the risk, accident, probability, consequence, length or duration of the routes and even shipment suspension could be among valuable future research directions.

5.3. Parameters and decisions

The parameters included in the formulation of HTND problems are provided in Table 23, wherein almost all of the papers, except Dadkar et al. (2010) and Su and Kwon (2020), have considered deterministic link travel costs. Indeed, due to several external factors (e.g., weather conditions or governmental regulations), the travel time and costs may be uncertain and change over time. Consequently, to develop more realistic HTND models, it is recommended as a future research direction to consider uncertain travel time and cost to model HTND problems. This consideration may require developing stochastic/robust models for HTND problems, which could be novel contributions to the literature. This issue is similar for the demand of hazmat shipments in the network, which has been mostly considered as a deterministic parameter, except in Chiou (2017). However, the demand is inherently uncertain in most real-world problems including HTND problems. Accordingly, taking the stochastic nature of the demand into account in the HTND problem could be another promising future research direction. Last but not the least, incorporating other parameters such as node population loss and weather conditions in the HTND problem are also worthy of further investigation.

The major decisions made in the HTND literature are presented in Table 24. In contrast to decisions made in HR and HRS problems, HTND problems contain a set of new decisions, so-called *transportation network design decisions*, taken by the government to force carriers to pursue the government objectives, which usually conflict with that of the carriers. As can be observed in Table 24, the paper of Esfandeh et al. (2017) is the only paper that makes scheduling-related decisions in the HTND problem. Two other important decisions that are worthy of investigation as future research are 1) fleet planning decisions in the HTND problem, and 2) analyzing the congestion of hazmat shipment in the network using queuing theory (Mohammadi et al., 2017). Although few papers have investigated the application of closing a specific set of links for shipping an OD flow to satisfy the government's objectives (Erkut & Alp, 2007b; Reilly et al., 2012; Su & Kwon, 2020), the application of link- or path-based toll pricing has not been studied in the literature. This aspect could be strengthened in the literature on the HTND problem through future research.

5.4. Modeling and solution techniques

The basic modeling and solution techniques applied in the HTND literature have been classified in Table 25. As can be seen

Table 20
Classification of articles studying HTND problems based on their assumptions.

Reference	Main Assumptions												
	Transportation mode	OD pairs' structure				Model players			Player competition type	Vehicle type		Multi/Single period	Multi/single hazmat classes
		Local routing	Global routing	Vehicle routing		Carrier	Government	Others		Homogenous	Heterogeneous		
				Single depot	Multiple depots								
Dadkar et al. (2010)	Road	*	–	–	–	*	*	–	St [d]	*	–	S	S
Kara and Verter, (2004)	Road	–	*	–	–	*	*	RA[b]	St	*	–	S	M
Erkut and Gzara (2008)	Road	–	*	–	–	*	*	–	St	*	–	S	S
Bianco et al. (2009))	Road	–	*	–	–	*	*[f]	LA[c]	St	*	–	S	M
Marcotte et al. (2009)	Road	–	*	–	–	*	*	–	St	*	–	S	M
Reilly et al. (2012)	Rail	–	*	–	–	*	*	–	St	*	–	S	S
Bianco et al. (2015)	Road	–	*	–	–	*[e]	*	–	St	*	–	S	S
Sun, Karwan and Kwon (2015)	Road	–	*	–	–	*	*	–	St	*	–	S	S
Assadipour et al. (2016)	MI[a]	–	*	–	–	*	*	–	St	-	*	S	S
Chiou (2016)	Road	–	*	–	–	*	*	–	St	*	–	S	S
Esfandeh, Kwon and Batta (2016)	Road	–	*	–	–	*	*	–	St	*	–	S	S
Kheirkhah et al. (2016b)	Road	–	–	*	–	*	*	–	St	*	–	S	M
Chiou (2017)	Road	–	*	–	–	*	*	–	St	*	–	S	S
Esfandeh et al. (2017)	Road	–	*	–	–	*	*	–	St	*	–	M	M
Fontaine and Minner (2018)	Road	–	*	–	–	*	*	–	St	*	–	S	S
Erkut and Alp (2007b)	Road	–	*	–	–	*	*	–	–	*	–	S	S
Verter and Kara (2008)	Road	–	*	–	–	*	*	–	–	*	–	S	M
Zhou et al. (2013)	Road	–	*	–	–	*	*	–	–	*	–	S	M
López-Ramos, Nasini and Guarnaschelli (2019)	Road	–	*	–	–	*	*	–	St	*	–	S	S
Jabbarzadeh et al. (2020)	Rail	–	*	–	–	*	–	RP[g]	–	–	*	S	S
Fontaine et al. (2020)	MI	–	*	–	–	*	*	–	St	*	–	S	S
Su and Kwon (2020)	Road	–	*	–	–	*	*	–	St	*	–	S	M
Ke et al. (2020)	Road		*			*	*		St	*		S	M
Statistics (%)	Road: 82 Rail: 9 MI: 9	4	92	4	0	100	96	12	88	91	9	S: 96 M: 4	S: 61 M: 39

a: MI stands for Multimodal or Intermodal (Rail-Truck), b: RA stands for Regulatory agencies, c: LA stands for Local authority d: Stackelberg, e: Carriers play a Nash game with each other, f: Regional authority, and g: RP stands for Railroad planners.

Table 21
Classification of articles studying HTND problems based on their objectives.

Player	Main objectives		Objectives: SOP or MOP
Government	Risk (Min)	Expected risk	SOP: Erkut and Alp (2007b), Verter and Kara (2008), Dadkar et al. (2010), Sun et al. (2015), Kheirkhah et al. (2016b)), Esfandeh et al. (2017), Fontaine and Minner (2018) MOP: Reilly et al. (2012), Zhou et al. (2013), Jabbarzadeh et al. (2020)
		Population exposure	SOP: Kara and Verter (2004), Erkut and Gzara (2008), Bianco et al. (2009)), Esfandeh et al. (2016) MOP: Marcotte et al. (2009), Bianco et al. (2015), Assadipour et al. (2016), López-Ramos et al. (2019), Ke et al. (2020)
		Maximum risk	SOP: Fontaine et al. (2020), MOR: Chiou (2016), Chiou (2017), Ke et al. (2020)
		(CVaR)	SOP: Su and Kwon (2020)
	Equity	Max: Risk on each link or zone	SOP: Bianco et al. (2009)) MOP: Bianco et al. (2015)
	Economic (Min)	Total travel time	MOP: Reilly et al. (2012)
		Total route length	MOP: Marcotte et al. (2009), Bianco et al. (2015)
		Maximum travel time	MOP: Chiou (2016), Chiou (2017)
		Toll costs	MOP: Marcotte et al. (2009), Assadipour et al. (2016)
		Total general cost	MOP: Jabbarzadeh et al. (2020), López-Ramos et al. (2019)
	Minimizing the total impact of lane reservation on normal traffic		MOP: Zhou et al. (2013)
Carriers	Risk (Min)	Expected risk	MOP: Reilly et al. (2012), Chiou (2016), Chiou (2017), Jabbarzadeh et al. (2020), Su and Kwon (2020)
		Population exposure	MOP: Marcotte et al. (2009)
	Economic (Min)	Total Monetary costs ($)	SOP: Assadipour et al. (2016)
		Total travel time	SOP: Dadkar et al. (2010), Sun et al. (2015), Esfandeh et al. (2016) MOP: Reilly et al. (2012), Chiou (2016), Chiou (2017), Su and Kwon (2020)
		Total route length	SOP: Kara and Verter (2004), Erkut and Alp (2007b), Verter and Kara (2008), Erkut and Gzara (2008) MOP: Marcotte et al. (2009), Bianco et al. (2015)
		Total general cost	SOP: Kheirkhah et al. (2016b)), Fontaine and Minner (2018), Fontaine et al. (2020) MOP: Jabbarzadeh et al. (2020), López-Ramos et al. (2019), Ke et al. (2020)
		Toll costs	MOP: Marcotte et al. (2009), Bianco et al. (2015), López-Ramos et al. (2019)

***Technical Comments**:* Bianco et al. (2009)) studied the HTND problem with two players as local and regional authorities, wherein the objective of the global authority is to minimize the total risk, and that of the local authority is to maximize the equity in its region. Marcotte et al. (2009) modeled the objectives of government and carriers as two different risk functions, the total incident cost, and the total toll cost, respectively. Zhou et al. (2013) considered the total travel time as the main carriers' concern and modeled it through constraints. This concern was modeled as an objective function in Assadipour et al. (2016) that consists of inbound and outbound drayage costs, rail-haul cost, fixed cost of operating different types of train services, and toll cost associated with the services provided by the original and destination terminals. Chiou (2016) and Chiou (2017) defined a measure as the general cost of each route, which is a function of the total travel time, the total delay, and the expected risk. Accordingly, the government aims at minimizing the maximum general cost over the routes, while the carriers minimize the sum of the total general costs over the routes. In the study done by Esfandeh et al., (2017), the carriers' problem does not include any objective function and the carriers' preferences were incorporated in the model through the constraints. López-Ramos et al. (2019) proposed a bi-level model where, in the upper level, the government' profit (toll income minus link addition and risk exposure costs) is maximized and in the lower level, the carriers' travel cost (travel congestion costs plus toll charges) is minimized. Jabbarzadeh et al. (2020) studied an HR problem considering the rail transportation mode under disruption, which inherently is an HTND problem since the authors considered the capacity planning of the rail links in their model, but no clear definition exists on the model's players and their specific objectives and the proposed model has only a single level with both risk and cost objectives. Su and Kwon (2020) proposed a probabilistic route choice model for the carriers' problem (i.e., 2nd-level problem), where the utilization of the routes depends on their risks and costs. Ke et al. (2020) propose a bi-level HTND problem In which the upper level has two objectives: minimizing total and maximum risk. Minimizing the maximum risk can provide risk equity in the model.

Table 22
Classification of articles studying HTND problems based on their constraints.

Main constraints	References
Equity for the risk on each link	Zhou et al. (2013)
Flow conservation constraints	Total references
The number of vehicles available	Kheirkhah et al. (2016b))
Time-window constraints	Zhou et al. (2013), Assadipour et al. (2016), Esfandeh et al. (2017), Jabbarzadeh et al. (2020)
Inaccessible roads	Kara and Verter (2004), Erkut and Alp (2007b), Verter and Kara (2008), Erkut and Gzara (2008), Dadkar et al. (2010), Reilly et al. (2012), Sun et al. (2015), Fontaine and Minner (2018), Fontaine et al. (2020), Su and Kwon (2020), López-Ramos et al. (2019)
Limiting the capacity of routes	Bianco et al. (2009)), Jabbarzadeh et al. (2020)
Signal setting constraints for intersections	Chiou (2016), Chiou (2017)
Budget constraint	Kheirkhah et al. (2016b)), López-Ramos et al. (2019)
Maximum toll level	López-Ramos et al. (2019), Ke et al. (2020)

in Table 25, heuristic and exact techniques are among the most popular/implemented solution algorithms for HTND problems with 30% and 56% contributions, respectively. As for metaheuristics, only two papers (Assadipour et al., 2016; Kheirkhah et al., 2016b) have, respectively, developed an evolutionary algorithm and particle swarm optimization algorithm to solve the HTND problem. Since heuristic or exact methods have their limitations when solving large-sized instances of HTND problems (i.e., heuristic algorithms do not, in general, provide good quality solutions and exact methods are computationally expensive), developing metaheuristic algorithms for different variants of the HTND problem definitely deserves careful investigation in the future.

Table 23
Classification of articles studying HTND problems based on their parameters.

Reference	Main input parameters and their types										
	Link's travel cost				Network demand	Link population loss	Links traffic flows	Rate of incidents	Accident severity	Incident probability	
	Economic costs ($)	Travel time	Length	general						Known	Unknown
Kara and Verter (2004)	–	–	DE	–	DE	DE	–	–	–	–	–
Erkut and Alp (2007b)	–	–	DE	–	DE	DE	–	–	–	DE	–
Verter and Kara (2008)	–	–	DE	–	DE	DE	–	–	–	DE	–
Erkut and Gzara (2008)	–	–	DE	–	DE	DE	–	–	–	–	–
Bianco et al. (2009))	–	–	–	–	DE	DE	–	–	–	–	–
Marcotte et al. (2009)	–	–	DE	–	DE	DE	–	–	–	–	–
Dadkar et al. (2010)	–	PR, DY	–	–	–	PR, DY	PR, DY	PR, DY	–	PR, DY	–
Reilly et al. (2012)	–	DE	–	–	DE	DE	–	–	–	DE	–
Zhou et al. (2013)	–	DE	–	–	DE	DE	–	–	–	DE	–
Bianco et al. (2015)	DE		DE	–	DE	DE	–	–	–	–	–
Sun et al. (2015)	–	DE	–	–	DE	–	–	UN[a]	UN	–	–
Assadipour et al. (2016)	DE	–	–	–	DE	DE	–	–	–	–	–
Chiou (2016)	–	DE	–	–	DE	DE	DE	–	–	–	DE
Esfandeh et al. (2016)	–	DE	–	–	DE	DE	DE	–	–	–	–
Kheirkhah et al. (2016b))	–	–	–	DE	DE	–	–	–	–	–	–
Chiou (2017)	–	DE	–	–	ST	DE	DE	–	–	–	DE
Esfandeh et al. (2017)	–	DE	–	–	DE	DE	DE	–	–	DE	–
Fontaine and Minner (2018)	–	–	–	DE	DE	DE	–	–	–	DE	–
Jabbarzadeh et al. (2020)	DE	–	–	–	DE	DE	–	–	–	DE	–
Fontaine et al. (2020)	–	–	–	DE	DE	DE	–	–	–	DE	–
Su and Kwon (2020)	–	PR	–	–	DE	DE	–	DE	–	DE	–
Ke et al. (2020)	DE	DE	–	–	DE	DE	–	–	–	–	–
López-Ramos et al. (2019)	DE	–	–	–	DE	DE	DE	–	–	–	–

Technica Comments: Dadkar et al. (2010) modeled the link's travel time as a function of the link's traffic volume. Zhou et al. (2013) differently modeled the travel time on reserved lanes and general lanes of the network links. Su and Kwon (2020) studied a probabilistic route choice model, wherein incident consequence and probability are deterministic. López-Ramos et al. (2019) converted risk and congestion to monetary costs. Also, the additional link cost was assumed to be a deterministic parameter. Ke et al. (2020) apply a set of thresholds on the maximum toll on each link for regular and hazmat shipments. Travel time is also converted to monetary cost by some parameters.
a: UN stands for Uncertain

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Table 24
Classification of articles studying HTND problems based on their decisions.

Reference	Main decision variables																
	Routing	Scheduling	Transportation network design decisions											Waiting decision		Vehicle decision	
			link restriction (general)	link restriction for each OD pair	link restriction for each hazmat type	Time-dependent link restriction	Link capacity limitation	Link capacity Expansion	Toll (general)	Toll for each hazmat type	Toll on terminals	Lane reservation	Signal setting	With queue discipline	Without queue discipline	Fleet assignment	Fleet planning
Kara and Verter (2004)	*	–	–	*	–	–	–	–	–	–	–	–	–	–	–	–	–
Erkut and Alp (2007b)	*	–	*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Verter and Kara (2008)	*	–	–	*	–	–	–	–	–	–	–	–	–	–	–	–	–
Erkut and Gzara (2008)	*	–	–	–	*	–	–	–	–	–	–	–	–	–	–	–	–
Bianco et al. (2009))	*	–	–	–	–	–	*	–	–	–	–	–	–	–	–	–	–
Marcotte et al. (2009)	*	–	–	–	–	–	–	–	–	*	–	–	–	–	–	–	–
Dadkar et al. (2010)	*	–	–	–	*	–	–	–	–	–	–	–	–	–	–	–	–
Reilly et al. (2012)	*	–	*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Zhou et al. (2013)	*	–	–	–	–	–	–	–	–	–	–	*	–	–	–	–	–
Bianco et al. (2015)	*	–	–	–	–	–	–	–	*	–	–	–	–	–	–	–	–
Sun et al. (2015)	*	–	–	*	–	–	–	–	–	–	–	–	–	–	–	–	–
Assadipour et al. (2016)	*	–	–	–	–	–	–	–	–	–	*	–	–	–	–	–	–
Chiou (2016)	*	–	–	–	–	–	–	–	–	–	–	–	*	–	–	–	–
Esfandeh et al. (2016)	*	–	–	–	–	–	–	–	*	–	–	–	–	–	–	–	–
Kheirkhah et al. (2016b))	*	–	–	–	–	–	–	–	*	–	–	–	–	–	–	*	–
Chiou (2017)	*	–	–	–	–	–	–	–	–	–	–	–	*	–	–	–	–
Esfandeh et al. (2017)	*	*	–	–	–	*	–	–	–	–	–	–	–	–	*	–	–
Fontaine and Minner (2018)	*	–	*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Jabbarzadeh et al. (2020)	*	–	–	–	–	–	–	*	–	–	–	–	–	–	–	*	–
Fontaine et al. (2020)	*	–	*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Su and Kwon (2020)	*	–	*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Ke et al. (2020)	*	–	–	–	–	–	–	–	–	*	–	–	–	–	–	–	–
López-Ramos et al. (2019)	*	–	–	–	*	–	–	–	*	–	–	–	–	–	–	*	–

Table 25
Classification of articles studying HTND problems based on their modeling/solution techniques.

Attribute		References
Basic modeling techniques	Demon approach	Nash game: Dadkar et al. (2010), Reilly et al. (2012), Stackelberg game: -
	Link-based formulation	Kara and Verter (2004), Erkut and Alp (2007b), Verter and Kara (2008), Bianco et al. (2009)), Marcotte et al. (2009), Zhou et al. (2013), Bianco et al. (2015), Sun et al. (2015), Esfandeh et al. (2016), Kheirkhah et al. (2016b)), Fontaine and Minner (2018), Fontaine et al. (2020), López-Ramos et al. (2019), Ke et al. (2020)
	Route-based formulation	Erkut and Gzara (2008), Dadkar et al. (2010), Reilly et al. (2012), Assadipour et al. (2016), Chiou (2016), Chiou (2017), Esfandeh et al. (2017), Jabbarzadeh et al. (2020), Su and Kwon (2020)
Solution techniques	Exact	Kara and Verter (2004), Erkut and Gzara (2008), Bianco et al. (2009)), Marcotte et al. (2009), Zhou et al. (2013), Jabbarzadeh et al. (2020), Fontaine et al. (2020)
	Heuristic	Erkut and Alp (2007b), Verter and Kara (2008), Bianco et al. (2009)), Dadkar et al. (2010), Reilly et al. (2012), Bianco et al. (2015), Sun et al. (2015), Chiou (2016), Esfandeh et al. (2016), Chiou (2017), Esfandeh et al. (2017), Fontaine and Minner (2018), Su and Kwon (2020), López-Ramos et al. (2019)
	Metaheuristic	Bi-level evolutionary algorithm: Assadipour et al. (2016) PSO: Kheirkhah et al. (2016b)) Genetic algorithm: Ke et al. (2020)

Technical Comments*:* Kara and Verter (2004) established Karush-Kuhn-Tucker (KKT) technique as an exact method to relax the 2nd-level problem. Bianco et al. (2015) developed an Old Bachelor Acceptance (OBA) approach as a heuristic algorithm to solve the HTND problem. Assadipour et al. (2016) solved the upper and lower levels of their proposed problem via a particle swarm optimization algorithm and CPLEX method, respectively. Chiou (2016) and Chiou (2017) proposed a heuristic bundle method, where generalized gradients are applied. Esfandeh et al. (2017) proposed a heuristic algorithm based on column-generation and label-setting.

5.5. Case studies

The details of the case studies investigated in the HTND literature are provided in Table 26. Table 26 shows that the HTND problem has only been considered in case studies in the U.S., Canada, and Italy. Among all cases, the largest real case study comes from the Lazio region of Italy with 311 nodes and 441 links, which is not as large as real case studies for the HR and HRS problems. For studying HTND problems, the Sioux Falls network is a classical benchmark, which has been used in 30% of the literature.

6. Discussion on HR, HRS, and htnd problems: similarities/dissimilarities

This section aims at providing an overall analysis of similar/dissimilar properties of HR, HRS, and HTND problems. In this section, we mostly discuss those properties for which obvious trends and tendencies can be observed when comparing these problems.

In terms of assumptions, road transportation is the predominant studied transportation mode in all three problems. Although rail and intermodal modes of transportation in HR problems have gained popularity with 13%, and 8% contributions, they have been rarely studied in the HRS and HTND literature. Regarding the maritime mode of transportation, it has been studied once in both HR and HRS problems, while not a single paper was found dealing with this mode of transportation in HTND problems. Finally, it was found out that the air mode of transportation has not been studied neither in HR nor in HRS and HTND problems.

It was observed that the local routing problem has been the most popular routing structure in the entire publications. However, in recent years, this structure has been replaced by global or vehicle routing structures. In HR and HRS problems, although global routing is often studied, a tendency towards the vehicle routing structure is obvious. In addition, this tendency has not still occurred in HTND problems. Despite two papers studying the HTND problem (Assadipour et al., 2016; Jabbarzadeh et al., 2020), considering a heterogeneous fleet is another property that has been regularly studied in almost all of the papers studying HR and HRS problems since 2008. As a particular property for HRS problems, the scheduling task has been mostly handled by designing a periodic model, where only 27% of the literature has incorporated the time through a single scheduling horizon. This property has been also studied in HTND problems (Esfandeh et al., 2017).

A property that has been at the core of attention in all problems is the class of hazmat. In this regard, multiple hazmat classes have been mostly considered rather than a single class of hazmat (i.e., with 13%, 27%, and 39% contributions in HR, HRS, and HTND problems, respectively). By looking at the papers studying multiple classes of hazmat over time, it was observed that despite HR and HRS problems, a significant tendency exists in HTND toward multiple classes of hazmat. This tendency is in line with what is occurring in the real world, where due to the increase in the demand and the number of classes of hazmat, carriers are now responsible for carrying more than a single class of hazmat shipments.

Most of the objectives and constraints that have been modeled in all problems are related to risk and economic concerns, where the contributions of equity and environmental concerns are very low particularly in the HRS and HTND problems. In contrast to the HRS problem, the HTND problem has been mostly studied from the viewpoint of the government (i.e., network planners) who is responsible for social and environmental issues besides risk and economic concerns. In this regard, few publications have studied equity objectives or constraints to address social concerns in the HTND problem (Bianco et al., 2009; Zhou et al., 2013, 2015). On the other hand, risk-related objectives and constraints have been mostly addressed through expected risk and population exposure measures; however, the contribution of CVaR, VaR, conditional probability, maximum risk, mean-variance, and disutility function measures is weak in the entire literature. While in the HR problem economic concerns have been mostly addressed through monetary objective functions (about 90% of the corresponding papers), in the HRS literature, travel time-related measures have often been incorporated to address economic concerns (about 67% of the corresponding papers). Regarding HTND problems, both monetary and travel time-related objective functions have been considered with similar rates.

Among the different categories of parameters, three of them have been frequently used in the entire literature including link-related, network-related, and incident-related categories of parameters. From these three categories, link population loss and link travel cost, network demand, and incident probability are the main parameters that have been usually used in each of the categories, respectively. However, the lack of other important categories of parameters is obvious in the literature, such as vehicle-related parameters (e.g., age, speed limit, load capacity, etc.) or even weather-related parameters (e.g., wind speed, temperature, and precipitation rate). Regarding the type of parameters, the stud-

Table 26
Classification of articles studying HTND problems based on their case studies.

Reference	Real cases					Hypothetical case					Data source		
	City/Country	Size				#Cases	Size				Real-life case	Random	Web reference
		#Nodes	#Links	#Routes	#Customers		#Nodes	#Links	#Routes	#Customers			
Kara and Verter (2004)	Western Ontario region of Canada	48	57	–	–	–	–	–	–	–	*	–	–
Erkut and Alp (2007b)	Ravenna city of Italy	105	134	–	–	–	–	–	–	–	*	–	–
Verter and Kara (2008)	Ravenna city of Italy	105	134	–	–	–	–	–	–	–	*	–	–
Erkut and Gzara (2008)	Two cases of Canada[a]	176	205	–	–	–	–	–	–	–	*	–	–
Bianco et al. (2009))	Lazio region of Italy	311	441	–	–	–	–	–	–	–	*	–	–
Marcotte et al. (2009)	Western Ontario region of Canada	48	57	–	–	–	–	–	–	–	*	–	–
Dadkar et al. (2010)	Jackson, MS to Tallahassee	604	–	600	–	–	22	34	100	–	*	*	–
Reilly et al. (2012)	Class I railroad the USA	–	–	11,000	–	–	–	–	–	–	*	–	–
Zhou et al. (2013)	Ravenna city of Italy	105	134	–	–	80	–	–	–	20	*	*	–
Bianco et al. (2015)	Ravenna city of Italy	105	134	–	–	–	10	13	–	–	*	*	–
Sun et al. (2015)	Ravenna city of Italy	105	134	–	–	–	–	–	–	–	*	–	–
Assadipour et al. (2016)	Norfolk Southern in the U.S.	NM	NM	–	–	–	–	–	–	–	*	–	*
Chiou (2016)	Sioux Falls	24	76	–	–	–	6	23	–	–	–	*	*
Esfandeh et al. (2016)	Sioux Falls	24	76	–	–	–	–	–	–	–	–	*	*
Kheirkhah et al. (2016b)	–	–	–	–	–	10	–	–	–	130	–	*	–
Chiou (2017)	Sioux Falls	24	76	–	–	–	6	23	–	–	–	*	*
Esfandeh et al. (2017)	Buffalo	90	149	–	–	–	–	–	–	–	*	*	–
Fontaine and Minner (2018)	Sioux Falls	24	76	–	–	–	–	–	–	–	–	*	*
Jabbarzadeh et al. (2020)	Class I railroad the USA[b]	25	53	1338	–	–	–	–	–	–	*	–	*
Fontaine et al. (2020)	Sioux Falls, and US & Canada[c]	24	76	–	–	–	–	–	–	–	–	–	–
Su and Kwon (2020)	Ravenna city of Italy	105	268	–	–	–	–	–	–	–	*	–	–
Ke et al. (2020)	Sioux Falls	24	76	–	–	–	–	–	–	–	–	*	*
López-Ramos et al. (2019)	Sioux Falls	24	76	–	–	–	–	–	–	–	–	*	*

a: (1): Western Ontario region of Canada and (2): Ontario and Quebec regions of Canada, b: only in the mid-west United States, c: the case US & Canada had 39 nodes and 122 directed links ies on HRS problems often consider dynamic parameters to relate them to scheduling decisions, while more than 95% of parameters are deterministic in HR and HTND problems. It is also worth mentioning that a considerable number of main parameters have not been considered under uncertainty in the literature; e.g., network demand, node population loss, and link travel cost in all the problems, incident probability in HR problems, and accident severity in HRS problems.

The common decisions made when addressing HR and HRS problems are the ones related to congestion-controlling decisions with/without queue discipline and fleet assignment. Although fleet planning has been studied in HR problems, its contribution is zero in HRS and HTND problems. Moreover, the fleet planning decisions in the literature highly focus on purchasing new vehicles, while fleet planning through leasing vehicles is worthy of investigation. A set of other decisions related to the transportation mode selection in intermodal networks or packing the hazmat with different classes in the vehicles, trains, vessels, or cargo planes have been studied neither in HR problems nor in HRS and HTND problems. The modeling of HTND problems includes a set of new decisions, transportation network design decisions, which are made by the government to force carriers to pursue the its own objectives (e.g., link closure or toll pricing) that conflict with the carriers' objectives. In this regard, setting tolls in conjunction with hazmat classes has been studied by Marcotte et al. (2009) and Ke, Zhang and Bookbinder (2020), but is not still used to network OD flows, paths, links, or a combination of them.

In terms of modeling, both link- and route-based formulations have been used equally by the researchers in the entire literature. On the other hand, only a few papers have proceeded with a multi-player game formulation including Kheirkhah et al. (2016b) and Mohri et al. (2020) who designed a Stackelberg game for HR and HRS problems, respectively, Szeto et al. (2017) who proposed a Nash game for an HRS problem, and Dadkar et al. (2010), Reilly et al. (2012) who designed a Nash game for an HTND problem. In terms of solution algorithms, several exact, heuristic, and metaheuristic algorithms have been developed in the literature, where the contribution of exact and heuristic solution algorithms is predominant for all problems. Genetic and Tabu search algorithms are the common metaheuristic algorithms applied to hazmat problems in more than half of the papers. In HR problems different metaheuristic algorithms (i.e., Genetic, Tabu search, GRASP, NSGA-II, and MODE) have been used, while Tabu search and ALNS are the only metaheuristic algorithms that have been applied in the HRS literature. Bi-level evolutionary and PSO algorithms are other metaheuristic algorithms that have been particularly developed for solving HTND problems.

An analysis of the employed case studies reveals that most of the cases belong to the U.S., where the networks of the city of Albany (N.Y.) and Class I railroads of the USA have been used frequently in hazmat road and rail transportation problems, respectively. In HR problems, nearly 18% of the literature has used case studies from other countries, rather than the U.S., including Italy, China, Chile, and India. This percent is higher for HRS and HTND problems with 50% and 38% contributions, respectively. In HRS problems, the case of the Singapore network is the predominant case compared to the cases from Italy and Greece. In HTND problems, the cases from outside the U.S. belong to Italy and Canada, where the network of Ravenna city of Italy has been employed in six different papers. Also, the Sioux Falls network is a popular benchmark for HTND problems that has been used in more than 30% of the papers. Although HR and HRS models have been tested on a set of large case studies with more than 5000 nodes and 3000 links, the largest case study in the HTND literature belongs to the Lazio region of Italy with 311 nodes and 441 links.

7. Hazmat transportation modes under scrutiny

As explained in Section 1.2, one of the main contributions of this paper is to discuss the role of transportation modes in HR, HRS, and HTND problems. Accordingly, this section provides the researchers with an overall view of the real-world hazmat transportation problems with different transportation modes.

Table 27 lists the reviewed papers studying different hazmat transportation problems with particular transportation modes. Based on the reviewed papers, it was observed that more than 90% of the literature on hazmat transportation problems is dedicated to road transportation mode. For instance, among the 90 reviewed papers, only 17 papers have studied other transportation modes. In the following, hazmat transportation is analyzed and discussed through rail, maritime, air, and intermodal modes of transportation.

7.1. Hazmat in rail transportation

The available statistics indicate that the volume of hazmat in rail transportation mode is increasing in developed countries. In the U.S., the total volume of crude oil and refined petroleum products hauled by the rail system was close to 725 and 1125 thousand barrels[1] in 2012 and 2015, respectively (U.S. Department of Energy, 2019). Moreover, in 2012, more than 110 million tons of other hazmat shipments were transported via the U.S.'s rail network (U.S. Department of Transportation, 2014), with a contribution of 4.3% among other transportation modes. In Canada, the total volume of hazmat on rail systems increased from 26.1 million tons in 2012 to 43.38 million tons in 2014 (Transport Canada, 2016). In Germany, 63 million tons of hazmat were shipped via railway system in 2010, representing 21% of the whole railway system's capacity (Fontaine et al., 2020). There exist indeed two reasons to justify such a continuously increasing trend: 1) the growing service provision of intermodal and multimodal freight transportation and 2) the recent need for shipping great volumes of crude oil and refined petroleum in the oil supply chain (Jabbarzadeh et al., 2020). Although the tonnage of hazmat on the road transportation mode is usually much more than rail transportation mode, hazmat ton-miles ratio in rail and road often do not have a big difference. For example, in the U.S., about 85 and 97 billion hazmat ton-miles were shipped by rail and road transportation in 2012, respectively (U.S. Department of Transportation, 2014). Indeed, hazmat shipments are often transferred in large volumes over long distances via railroads (Glickman et al., 2007).

While the railroad is one of the safest transportation modes with a very small incidents probability, the incidents' consequences may be very severe due to the existence of a large volume of hazmat over long distances. In this context, the terrorist threat is worrisome when hazmat shipments such as nuclear or radioactive materials are on the train (Glickman et al., 2007). Any unfortunate accident in this context may have a significant negative influence on public opinion and reduce the contribution of rail transportation in passengers and cargo transportation. Such events can also raise serious environmental concerns leading to a high pressure on carriers to outweigh and prioritize the social and environmental issues to economic ones when routing the hazmat (Verma, Verter & Gendreau, 2011).

Railway networks have a lower density in comparison with road networks; hence, fewer routing scenarios can be found for shipping an OD flow on a rail system compared to a road network.

[1] A barrel unit of volume is equal to 42 U.S. gallons.

Table 27
Papers on HR, HRS, HTND problems studying different transportation modes.

Problem	Transportation mode	References
HR	Road	Abkowitz and Cheng (1988), Batta and Chiu (1988), Gopalan et al. (1990), Klein (1991), Lindner-Dutton et al. (1991), Wijeratne et al. (1993), Beroggi (1994), Patel and Horowitz (1994), Beroggi and Wallace (1995), Karkazis and Boffey (1995), Jin et al. (1996), Jin and Batta (1997), Nembhard and White Iii (1997), Sherali et al. (1997), Verter and Erkut (1997), Marianov (1998), Nembhard and White Iii (1999), Erkut and Ingolfsson (2000), Frank et al. (2000), Dell'Olmo et al. (2005), Serafini (2006), Carotenuto et al. (2007a), Dadkar et al. (2008), Martí et al. (2009), Lozano et al. (2011), Hamdi-Dhaoui et al. (2014), Kang et al. (2014a), Kang et al. (2014b), Kheirkhah et al. (2016b), Teoh et al. (2016), Toumazis and Kwon (2016), Zhao and Zhu (2016), Kumar et al. (2018), Wang et al. (2018), Bronfman et al. (2015), Fan et al. (2015), Bronfman et al. (2016), Garrido and Bronfman (2017), Timajchi et al. (2019), Zhang et al. (2018)
	Rail	Glickman (1983), Glickman et al. (2007), Verma (2009), Verma et al. (2011), Hosseini and Verma (2017), Hosseini and Verma (2018), Hosseini and Verma (2021)
	Multimodal or Intermodal (Rail-Truck)	Verma and Verter (2010), Verma et al. (2012), Assadipour et al. (2015), Ke (2020)
	Maritime	Iakovou et al. (1999)
HRS	Road	Nozick et al. (1997), Zografos and Androutsopoulos (2004), Chang et al. (2005), Akgün et al. (2007), Carotenuto et al. (2007b), Erkut and Alp (2007a), Zografos and Androutsopoulos (2008), Androutsopoulos and Zografos (2010), Ma et al. (2012), Toumazis and Kwon (2013), Faghih-Roohi et al. (2016), Szeto et al. (2017), Mohri et al. (2020)
	Rail	Fang et al. (2017)
	Maritime	Siddiqui and Verma (2015)
HTND	Road	Bianco et al. (2009), Dadkar et al. (2010), Zhou et al. (2013), Bianco et al. (2015), Esfandeh et al. (2017), Fontaine and Minner (2018), Kara and Verter (2004), Erkut and Alp (2007b), Verter and Kara (2008), Erkut and Gzara (2008), Marcotte et al. (2009), Sun et al. (2015), Chiou (2016), Esfandeh et al. (2016), Kheirkhah et al. (2016b), Chiou (2017), Su and Kwon (2020), López-Ramos et al. (2019)
	Rail	Reilly et al. (2012), Jabbarzadeh et al. (2020)
	Multimodal or Intermodal (Rail-Truck)	Assadipour et al. (2016), Fontaine et al. (2020)

Moreover, since train wagons, whether including hazmat or not, may have different destinations, finding practical alternative routes would not be possible. This also makes the shipment scheduling task difficult since the risk of hazmat should be considered in the scheduling plan. It has been reported in the literature that with or without scheduling, rail networks are more vulnerable than road networks. Indeed, any disruption may render a big segment of the rail network unavailable (Jabbarzadeh et al., 2020). These disruptions in rail movements increase the carrier's cost due to rescheduling decisions and re-routing a part of the demand (i.e., freight or passengers) through the network or even shifting the demand to other available transportation modes.

Rail hazmat transportation is usually an inter-regional movement that is far from populated and circumvents metropolitan areas with a greater radius than the beltways. Therefore, the risk of incidents should be assessed only for stations, some rare links placed in the metropolitan areas due to urban development, the passenger cars mixed with hazmat cars on a train, and the passenger trains adjacent to the hazmat trains. For the latter one, the passenger trains should be treated as a mobile population area for the hazmat trains.

Accidents like train collisions (i.e., specifically collisions between a passenger train and a hazmat freight train), train-car collisions, and derailment can cause hazmat incidents. It has been revealed in the literature that the number of accidents is correlated with the train's speed, track quality, length, and climatic states (i.e., rain and snow) (Fang et al., 2017; Barkan, Dick & Anderson, 2003; Glickman et al., 2007). Moreover, the severity of hazmat incidents is correlated with the train's speed, the volume and type of hazmat shipments on the train, and windy weather conditions (Fang et al., 2017; Verma et al., 2011). In contrary to hazmat transportation by trucks, trains can carry multiple classes of hazmat. Hence, the release and mixture of different hazmat in an incident can intensify the severity of the incident (Verma & Verter, 2007). Furthermore, a windy weather condition can spread the hazmat or extend the affected area leading to an intensified negative consequence. Accordingly, Fang et al. (2017) and Verma et al. (2011) applied air dispersion models to measure the hazmat incident consequences in a rail system more meticulously.

A single shipment in a rail system can be transferred by multiple carriers that may cause inefficiency in the global route selection process when each carrier attempts to maximize its portion of the movement (McClure, Brentlinger, Drago & Kerr, 1988). Moreover, redirecting rail shipments from one carrier to another with all extra operations (e.g., unloading/loading, deconsolidation/consolidation, etc.) might disrupt train schedules (Glickman et al., 2007). Usually, dispatching passenger trains from either origin or intermediate stations has higher priority compared to freight trains because when a freight train reaches a station, it may be kept for a while; hence, passenger trains are dispatched first to minimize the delay of the passengers. On the other hand, the freight trains should wait until the passenger trains are dispatched. These waiting times increase the cost and the risk of the hazmat freight trains, particularly in the train stations. Therefore, the length of the rail routes cannot accurately represent the routes' costs and risks, and the waiting times at stations should be also considered in future research works (Mohammadi et al., 2017; Loza-Hernandez & Gendreau, 2020).

The physical infrastructure of a rail transportation network usually consists of rail yards (i.e., stations) and tracks (i.e., service legs). Certain yards are fully equipped for consolidation and deconsolidation activities while others may only provide block swap (transfer) operations (Verma et al., 2011). The volume of hazmat varies in trains while the trucks transport a fixed volume of a specific material. Assigning the majority number of a train's wagon to hazmat shipments indeed increases the risk of incidents along the rail route though it would decrease routing and delay costs. Accordingly, to make a trade-off between risk and cost, freight forwarders should carefully (i.e., optimally) determine the number of wagons dedicated to hazmat shipments. The maximum permitted number of wagons also depends on the locomotive power, route length, and route topology. For instance, shipping hazmat on longer and mountainous routes reduces the number of permitted wagons for a train.

7.2. Hazmat in maritime transportation

It was discussed earlier in this paper that the main objectives of hazmat transportation considering the maritime mode of transportation are minimizing the cost and the risk of transportation. In a maritime mode of transportation, the cost between an OD pair mainly depends on the traveled distance and vessel size (Iakovou et al., 1999), but this cost should also account for the return trip cost, because empty oil tankers must return to their origins (Iakovou et al., 1999). The links applied for loaded-leg may be different from those for ballast-leg, carrying just the bunker fuel. Moreover, in some cases, the renting costs for vessels and the waiting cost in origin and destination ports due to scheduling decisions should be of concern (Achurra-Gonzalez et al., 2016).

Assessing the transportation risk in maritime modes of transportation requires involving the vessel accidents causing a leak for liquid hazmat (e.g., oil), which leads to high economic and environmental damages. Vessel collision, natural disasters like earthquake, tsunamis, and hurricane, terrorists' attacks, vandalism, war, and grounding due to different reasons such as waves, wind, depth of waterway, the geometry of waterway, tide, vessel age, visibility, darkness, speed, and human factors all constitute the causes for a hazmat leak (Kite-Powell, Jin, Jebsen, Papakonstantinou & Patrikalakis, 1999; Jebsen & Papakonstantinou, 1997; Samuelides, Ventikos & Gemelos, 2009; Briggs, Borgman & Bratteland, 2003). Accordingly, assessing different possibilities of causes can highly affect the measurement of the incident probability and consequently the risk associated with hazmat-leak events.

On the other hand, hazmat-leak-related costs consist of economic and environmental costs. Economic costs include the costs of cleanup, indemnification charges, and those imposed on fishing and tourism industries (Siddiqui and Verma, 2013). These costs may make a hazmat transporter bankrupt (Siddiqui and Verma, 2013). For instance, the harmful impacts of oil leak on fish, shellfish, mammals, marine birds, wildfire habitats, and mangrove forests constitute the environmental costs (Noaa, 2019; Mohit, 2019). Furthermore, hazmat-leak-related costs are a function of the leak rate, while full leakage does not occur all the time.

Economic of scale dictates the supertankers' services in transporting the hazmat shipments, while these cannot arrive/depart to/from some ports with no special features like water depth to dock. Therefore, they can begin or end their trips within offshore zones, where the hazmat (e.g., oil) is transferred from supertankers to smaller tankers or vice versa (Iakovou et al., 1999). As a result, the vessel size can affect the risk and the cost of maritime routes. In the maritime mode of transportation, the capacity of ports and liner services are limited; hence, capacity constraints are necessary for hazmat transportation problems.

An overall analysis revealed that oil products are the main types of hazmat in maritime transportation. Oil products are of two categories: (1) crude oil and (2) refined and processed petroleum products such as gasoline, Orimulsion, liquid natural gas, distillate, etc. (Iakovou et al., 1999). In 2018, 11 billion tons of hazmat were traded through the sea, which was 28.6% of the total maritime trade (UNCTAD, 2019). The oil supply chain is of three: (1) upstream, (2) midstream and (3) downstream segments (Lima, Relvas & Barbosa-Póvoa, 2016). Shipping crude oil and refined petroleum products through the sea are categorized into upstream and downstream segments, respectively, starting from and ending to oil terminals.

7.3. Hazmat in air transportation

Some non-hazmat shipments when transported on land become hazmat when transported through an airway system. For instance, lithium batteries and aerosol cans are two classes of hazmat in the air while they represent no hazard on land (Marten, 2015). The atmosphere around an airplane can highly cause fluctuations in air pressure, temperature, static electricity, and vibration, and all of these can cause a reaction in the hazmat shipments, which can be threatening. On 28 July 2011, a cargo plane, carrying a total of 58 tons of newly manufactured electronic products including lithium batteries and mobile phones caught fire and fell in the sea on the Seoul-Shanghai route. The main reason for the incident was a fire in the aircraft's cargo hold (1001 Crash, 2015). Accordingly, International Air Transport Association (IATA) has pinpointed hazmat shipments through an airway network and forced airlines to follow certain regulations in terms of shipping this cargo (IATA, 2010).

To the best of our knowledge, no paper was found to study the hazmat transportation problem considering air mode of transportation. This consideration can be a promising future research direction due to the following reasons:

- There exists a rising demand for technological gadgets all over the world. Since these products have high values, shipping them by aircraft would be the most economical way (Hsu, Huang & Tseng, 2016).
- Only certain developed countries such as U.S. and China have the technology for mass production of these gadgets; hence, their transportation is not localized and it leads to increase demand for air transportation from developed countries to other demand points around the world.

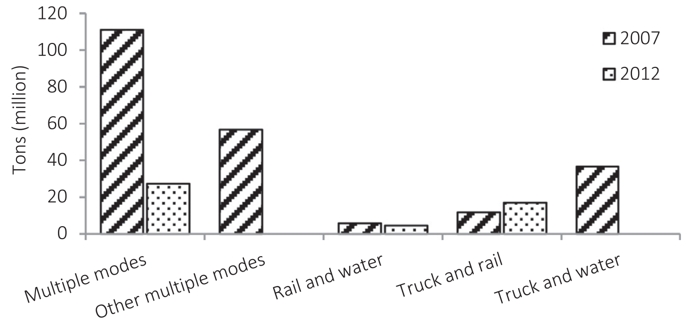

Fig. 2. The contribution of multiple modes in shipping hazmat in 2007 and 2012 (U.S. Census Bureau, 2012).

7.4. Hazmat in intermodal transportation

The statistics of shipping hazmat in the U.S. via multiple modes of transportation in 2007 and 2012, which are obtained from the latest accessible statistics (U.S. Census Bureau, 2012), have been depicted in Fig. 2, wherein a decreasing trend is evident. However, in 2012, almost 17 million tons of hazmat were shipped through truck-rail mode; while in 2007, this value was 12 million. Moreover, shipping hazmat through the rail-water mode of transportation sums up to a total of 5 million tons. Therefore, although the overall trend is decreasing, shipping hazmat through combining rail with truck or water has gained its importance.

Shipping hazmat through multiple modes (e.g., truck and rail in specific) can optimize cost and risk measures significantly. The cost will be reduced due to scale economies associated with railroads especially operating between two intermodal freight stations. On the other hand, trucks collecting/distributing hazmat to/from intermodal stations improve the accessibility of intermodal services (Assadipour et al., 2016). The risk will be also optimized because a considerable portion of trips is made by intermodal rail services that are safer than truck services. In this context, calculating the risk during an intermodal trip needs more attention. Since the number of hazmat containers and the classes of hazmat vary among intermodal freight trains, the risk measure should be a function of the volume and the class of hazmat shipments.

An intermodal mode of transportation involves three processes as inbound drayage, rail haul, and outbound drayage. Rail haul services in an intermodal network are non-stop, fixed-scheduled, and punctual, whereby they are quite different from those in rail networks (Nozick & Morlok, 1997; Verma & Verter, 2010). Moreover, intermodal units must be carried on appropriate flat railcars, matched with the intermodal units (Bontekoning et al., 2004). Observing lead time for intermodal freights (e.g., hazmat) is an important factor in designing the length and assortment of intermodal trains (Verma & Verter, 2010). Furthermore, the congestion in intermodal stations, especially when hazmat shipments are waiting in a queue, can increase the risk of hazmat incidents (Mohammadi et al., 2017). Therefore, to calculate the hazmat incident risk imposed on intermodal stations, congestion should be investigated. Moreover, to dispatch hazmat from intermodal stations under congestion, queuing theory can step in to evaluate the congestion of hazmat (Assadipour, Ke & Verma, 2015; Mohammadi et al., 2017).

8. Conclusions and future research directions

This paper provided a comprehensive review in the domain of hazmat transportation from an Operational Research viewpoint. In this regard, three hazmat routing (HR), hazmat routing-scheduling (HRS), and hazmat transportation network design (HTND) problems have been reviewed in detail from the literature including the high-quality papers published in leading journals from 1980 to the end of July 2021. To the best of our knowledge, Erkut et al. (2007) has been the only paper that offers a comprehensive and fairly recent review in hazmat transportation from an Operational Research viewpoint. Accordingly, we believed this domain deserves an up-to-date comprehensive analysis of the literature to review the proposed models and solution approaches. This review was conducted in two levels. First, the papers studying each of these problems are classified in terms of models' assumptions, objectives and constraints, decisions, input parameters, basic modeling/solution techniques, and case studies. Besides, the most significant research gaps in the literature for each class of problems are identified through a systematic in-depth review at a micro-level. Finally, a set of promising future research directions are proposed for each class of problems upon which the authorities could draw better decisions. Second, the specific features of different transportation modes are comprehensively explained when studying hazmat transportation problems.

In addition to future research propositions specific to each class of problems, there exist still a set of general future research directions in the domain of hazmat transportation problems. Indeed, any future research in this domain should embody: 1) what the hazmat transportation problem (i.e., HR, HRS, and HTND) should be in terms of modeling, and (2) what the hazmat transportation mode should be (e.g., road, rail, maritime or airway). Consequently, in the following, a set of general future research directions are suggested.

First, the future work directions on modeling the hazmat transportation problems are provided as follows:

- There exist approaches for spreading the risk among different regions of a network and providing equity despite the historical damages and consequences in the regions. Classically, it has been assumed that all regions are in the same equity condition, and the equity is provided only for the planning period. However, some of the regions in the network may experience more severe consequences, while others are safe. Accordingly, the total historical hazmat consequences that each region has tolerated would be worthy of consideration in future studies.
- From the insurance company's viewpoint, these companies can encourage the carriers to put more emphasis on the risk objectives vs. economic objectives. This can be achieved through: compensating the incident costs only for a specific set of network links, partially compensating the incident costs on a set of the network links, or increasing the insurance costs for incidents occurring on risky links. Moreover, assessing the income changes of insurance companies, and the changes of risk and economic objectives could be among future studies in this regard.
- In the relevant literature, the radius or bandwidth of the affected area around the network links for estimating the link consequences is considered to be fixed. In this estimation, only the population of the corresponding area is of concern, while the population outside the area is not. Since the severity of consequences decreases by getting far from the incident center, researchers may hierarchically estimate the impact of an incident on an area.
- It is revealed that only horizontal equity measures have been studied in the studied hazmat transportation problems. Developing a vertical equity measure for spreading the risk in the network could be also worthy of investigation.
- Some of the network links have facilities nearby such as gas stations that intensify the consequence of a hazmat incident on those links. In this situation, when estimating the risk of an incident on a link, the impact of its nearby facilities should be also considered.
- For the studies considering a known incident probability for the network links, the targeted period used for calculating the incident probability based on historical incident records should be determined precisely. For this aim, first, the climatic changes and road traffic volume over the considered period should be low and, next, the physical conditions of the link over the period should not be subjected to significant changes such as safety improvement projects.
- In addition to reducing the risk imposed on the population, the government should be concerned with the costs imposed on users in the road network by closing a link for a while due to hazmat incidents. Some of the network links such as bridges or tunnels are very critical and closing them would increase the total travel time in the network. In this regard, researchers should focus on an HTND problem where the government seeks to decrease the risk of incidents on vulnerable links of the network.
- The population in the nodes (e.g., stations of a rail network) may change over time because these facilities serve both the freight and passenger trains. When a passenger train is boarding or alighting passengers in a station, the station is crowded. For an HRS problem with rail transportation mode, the population in the stations should depend on the timetable of passenger trains. This can reduce the risk to the population.
- In a set of studies on HR problems, the objective has been maximizing the distances between hazmat vehicles on the network links and a set of vulnerable centers. This approach does not consider any difference between various vulnerable centers such as schools, libraries, big buildings, and hospitals. This modification can be done by maximizing weighted distances between hazmat vehicles and the vulnerable centers, where the weights depend on the vulnerability degree of the centers, hazmat classes, vehicle type, and weather conditions. Accordingly, minimizing the total or maximum distance between hazmat vehicles and the existed emergency centers in the network can be a new objective for all HR, HRS, and HTND problems. This objective can be applied only for the high-risk links to assure that the emergency service will reach the venue with less incident delay, and efficiently mitigate the undesirable consequences.

- The related literature on HTND problems indicates that there exist three approaches for toll pricing: (1) a general toll for all carriers, hazmat classes, vehicle types, etc., (2) a specific toll for each hazmat class, and (3) a toll as a function of hazmat volume on the links of the network. In this paper, two new approaches for toll pricing are suggested. First, the toll volume considered for traversing a link should be customized for each carrier or OD pair, which would purposefully prevent the carriers or OD pairs from posing a high risk to the population around the link. Second, the toll considered for traversing a link should be time-dependent to encourage carriers to move their shipments in specific periods of a day or spreading them between different periods.
- In HTND problems, certain studies simultaneously minimize the toll and the total risk on the links of the network through the government's problem (1st-level problem), while these studies do not adjust the toll volume equitably between different hazmat carriers. For instance, adding a toll on a link can increase the economic costs of carriers A and B by 2% and 5%, respectively. To achieve fairness between carriers, the toll should be customized for each carrier, which can be a direction for future studies. Moreover, the carriers should be treated fairly in adopting other policies/decisions such as lane restriction, lane reservation, or terminal pricing.
- The human factor is among the most influential factor in road accidents. The government should prohibit aggressive drivers from driving on high-risk links. Link restriction or toll pricing policies in HTND problems should be applied for different categories of drivers, according to their driving records. As a result, drivers with bad records should be either prevented from traveling on high-risk links by closing or tolling the links for them.
- Restricting the hazmat volume on the links of the network in different periods in HTND problems can be another policy for the government to mitigate the total risk in the network, where the remaining volume of hazmat on a given link can be communicated with other drivers by Variable-Message Sign (VMS) boards at the beginning of the link. Furthermore, rather than closing a link after reaching its hazmat capacity (a hard restriction), the government can investigate the impact of assigning a high toll on it (a soft restriction).
- Last but not least, the integration of machine learning techniques into metaheuristics has shown a promising research direction in solving combinatorial optimization problems (Karimi-Mamaghan et al., 2020a, 2020b; Karimi-Mamaghan, Pasdeloup, Mohammadi & Meyer, 2021a, 2021b), including hazmat transportation problems. Accordingly, the readers are also encouraged to develop learning-based metaheuristics and investigate how machine learning techniques can contribute to the resolution of such problems.
- Second, the future work directions on hazmat transportation modes are provided as follows:
- The use of the maritime mode of transportation has been ignored in the HTND literature. However, governments can pursue different strategies including link closure and toll pricing to meet social and environmental objectives.
- In maritime transportation, the number of appropriate links to ship oil products and consequently the number of routing scenarios between OD pairs are limited. It is assumed that routing-scheduling problems can act better than pure routing problems to reduce the cost and the risk objectives.
- Incorporating climatic conditions including wind and wave speeds, visibility, darkness, and waterway features like depth and geometry for maritime routing and scheduling scenarios are necessary since they can affect the accident probability for oil vessels.
- Most businesses and governments across the world that their industries are dependent on oil flow are concerned with unprecedented disruptions in the oil supply chain, which may cause losing the market share for businesses or a strike for governments. These entities are willing to invest in the projects leading to a resilient supply chain. For instance, Japan and Saudi Arabia have recently agreed to renew a joint crude oil storage scheme in Okinawa, an action that gives the Middle East supplier quick access to its key customers in East Asia, while providing energy security for Tokyo (Kumagai, 2019). Theretofore, designing a resilient hazmat transportation network for maritime oil products could be an interesting future research direction.

Appendix A. Journal quality filtration procedure

Three journal classification systems including Australian Business Deans Council 2016 (ABDC), Academic Journal Guide 2018 (AJG), and Financial Times (FT) were used to select the top journals and consequently the high-qualified papers published in the scope of this paper. In the ABDC system, journals are rated in four categories, A*, A, B, and C, while in the AJG system, there are five: 4*, 4, 3, 2, and 1. The journals in FT consist of 50 top journals involved in Business School Research Rankings. All A* or A ranked journals in the ABDC system, 4*, 4, or 3 ranked journals in the AJG system and the FT ranked journals that are related to the fields of *Operations Research*, *Management Science*, *Transportation*, and *Logistics* are searched in this paper. The targeted journal list, in alphabetic order, is as follows:

- Accident Analysis and Prevention
- Annals of Operations Research
- Computational Optimization and Applications
- Computers and Operations Research
- Decision Sciences
- Decision Support Systems
- European Journal of Operational Research
- Evolutionary Computation
- IEEE Transactions
- International Journal of Production Economics
- International Journal of Production Research
- Journal of Management
- Journal of Supply Chain Management
- Journal of the Operational Research Society
- Location Science
- Management Science
- Manufacturing and Service Operations Management
- Mathematics of Operations Research
- Mathematical Programming
- OMEGA: The International Journal of Management Science
- Operations Research
- OR Spectrum
- Production and Operations Management
- SIAM Journal of Optimization
- Transportation
- Transportation Research Part A
- Transportation Research Part B
- Transportation Research Part C
- Transportation Research Part D
- Transportation Research Part E
- Transportation Science

Appendix B. Basic mathematical models of HR, HRS, and HTND problems

A basic HR model: Gopalan et al. (1990) proposed the basic mathematical model of a hazmat local routing problem, wherein the equity of risk is fulfilled via constraints of the model over geographical zones of the network. For the sake of simplicity, the equity constraint is excluded from the presented mathematical model. The mathematical model (B1)-(B4) is a single-objective model that minimizes the total expected risk in the network. The expected risk is the multiplication of the incident probability and its consequence. The incident consequence is estimated by the λ-neighborhood concept. The notations and the mathematical model of the hazmat local routing problem are expressed as follows: *Sets and indices*

A Set of arcs

N Set of nodes

t Index for network trips
$i,\ j$ Indices for network nodes

Parameters

T Total trips made in the network from origin nodes O to destination nodes D
O The origin of HAZMATs
D The destination of HAZMATs
C_{ij} The total risk of traveling on link (i, j)

Variables

x_{ijt} 1 if link (i, j) is used on the t^{th} trip; 0 otherwise.

$$Min \sum_{t=1}^{T} \sum_{(i,j)\in A} C_{ij}x_{ijt} \tag{B1}$$

s.t.:

$$\sum_{j} x_{ijt} - \sum_{j} x_{jit} = \{\begin{matrix} 1 \ if \ i=O \\ -1 \ if \ i=D \forall \ i=1,\ldots,\ |N| and \ t=1,\ldots,\ T \\ 0 \ otherwise \end{matrix} \tag{B2}$$

$$\sum_{j} x_{ijt} \le 1 \ \forall \ i=1,\ldots,\ |N| \ and \ t=1,\ldots,\ T \tag{B3}$$

$$x_{ijt} \in \{0,1\} \forall \ i=1,\ldots,|N| and \ t=1,\ldots,\ T \tag{B4}$$

The objective function (B1) minimizes the total risk made by the trips on the links of the network. Constraints (B2) and (B3) are flow conservation constraints, and constraint (B4) shows the domain of the decision variables.

A basic HRS model: A basic mathematical model of the HRS problem is one presented by Erkut and Alp (2007a). This model has only one OD pair and the origin and destination nodes are presented as nodes 1 and N, respectively. The model's objective function minimizes the total expected risk of hazmat shipments through the network links. The risk on the network links also varies over periods. Before presenting the mathematical model (B5)-(B11), the notations are explained as follows: *Sets and indices*

$G(V,E)$ A directed graph where V and E are the sets of nodes and links, respectively
i, j Indices of network nodes where (i, j) represents a network link
t Index of arriving time of the hazmat shipment to the network nodes
N Number of nodes (nodes N is the destination)
m Number of links
$P(i)$ Set of predecessor nodes of node$i$
$S(i)$ Set of successor nodes of node$i$

Parameters

$d_{ij}(t)$ Duration of link (i, j) at arriving time t
$r_{ij}(t)$ Risk on link (i, j) at arriving time t
T Maximum allowed duration of the selected route

Variables

X_{ijt} 1 if link (i, j) with arriving time t is a part of the selected route; 0 otherwise.

$$Min \sum_{t=1}^{T} \sum_{(i,j)\in E} r_{ij}(t)X_{ijt} \tag{B5}$$

s.t. :

$$\sum_{t=1}^{T} \sum_{i\in S(1)} X_{1it} = 1 \tag{B6}$$

$$\sum_{t=1}^{T} \sum_{i\in P(N)} X_{iNt} = 1 \tag{B7}$$

$$\sum_{t=1}^{T} \sum_{j\in S(i)} X_{ijt} - \sum_{t=1}^{T} \sum_{j\in P(i)} X_{jit} = 0 \ \forall i=2,\ldots,\ N-1 \tag{B8}$$

$$\sum_{t=1}^{T} \sum_{j\in P(i)} X_{jit}\left(t+d_{ji}(t)\right) \le \sum_{t=1}^{T} \sum_{j\in S(i)} X_{ijt}(t) \forall i=2,\ldots,\ N-1 \tag{B9}$$

$$\sum_{t=1}^{T} \sum_{i\in P(N)} X_{iNt}(t+d_{iN}(t)) \le T \tag{B10}$$

$$X_{ijt} \in \{0,1\} \forall \ i, j, t \tag{B11}$$

The objective function (B5) minimizes the total risk imposed by the hazmat shipments to the network. Eqs. (B6), (B7), and (B8) are the flow conservation constraints. The difference between departure time from the beginning to the end of the network links is always greater than or equal to the duration of the traveling on the link, guaranteed through Eq. (B9). Eq. (B10) ensures that the total duration on a selected route should be less or equal to T. Finally, Constraint (B11) presents the domain of the decision variables.

A basic HTND model: The first mathematical model for addressing the HTND problem was presented by Kara and Verter (2004), wherein multiple classes of hazmat and multiple OD pairs have been considered. The proposed model involves a bi-level structure, where the outer and inner problems correspond to the government and the carriers, respectively. In this model, the government seeks to minimize the total number of the population exposed to the danger of hazmat incidents through closing certain links in the network, while carriers minimize the total travel length as an economic objective. The notation and mathematical form of the model are explained as follows: *Sets and indices*

$G(N,A)$ Graph of the network with N and A as the sets of nodes and links, respectively
M Set of HAZMAT classes
P Set of population centers, (i.e. a bandwidth around network links)
C Set of shipments
i, j, k Indices of nodes and (i, j) represents the link between nodes i and j
m Index of HAZMAT classes
p Index of population centers
c Index of shipments
$o(c)$ Origin node of shipment c
$d(c)$ Destination node of shipment c
$m(c)$ HAZMAT class of shipment c

Parameters

$\rho_{ij}^{p,m}$ Number of the population exposed to any incident in population center p when a truck is hauling HAZMAT class m on link (i, j)
l_{ij} Length of link (i, j)
n^c Number of required trucks for transporting shipment c

Variables

Y_{ij}^{m} 1 if link (i, j) is permitted to transport HAZMAT type m; 0 otherwise
X_{ij}^{c} 1 if link (i, j) is utilized for transporting shipment c; 0 otherwise

$$\min_{Y_{ij}^{m}\in\{0,1\}} \sum_{p\in P} \sum_{(i,j)\in A} \sum_{c\in C} n^c \rho_{ij}^{p,m(c)} X_{ij}^{c} \tag{B12}$$

where X_{ij}^{c} is the solution of the following problem (2nd-level problem) when Y_{ij}^{m} is fixed, and

$$\min \sum_{c \in C} \sum_{(i,j) \in A} n^c l_{ij} X_{ij}^{c} \tag{B13}$$

subject to :

$$\sum_{(i,k) \in A}^{T} X_{ik}^{c} - \sum_{(k,i) \in A}^{T} X_{ki}^{c} = \{ \begin{array}{l} +1 \ if \ i = o(c) \\ -1 \ if \ i = d(c) \\ 0 \ otherwise \end{array} \forall \, i \in N, \ c \in C \tag{B14}$$

$$X_{ij}^{c} \leq Y_{ij}^{m(c)} \forall (i,j) \in A, \ c \in C \tag{B15}$$

$$X_{ij}^{c} \in \{0,1\} \forall (i,j) \in A, \ c \in C \tag{B16}$$

Objective functions (B12) and (B13) are the government and carriers' objectives that minimize the total population exposed to any risk and the total travel length in the network, respectively. Eq. (B14) is the flow conservation constraint. Constraint (B15) ensures that carriers cannot select the links closed by the government. Finally, constraint (B16) expresses the domain of the decision variables.

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