Hazardous Materials Transportation: a Literature Review and an Annotated Bibliography

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Abstract. The hazardous materials transportation poses risks to life, health, property, and the environment due to the possibility of an unintentional release. We present a bibliographic survey on this argument paying particular attention to the road transportation. We attempt to encompass both theoretical and application oriented works. Research on this topic is spread over the broad spectrum of computer science and the literature has an operations research and quantitative risk assessment focus. The models present in the literature vary from simple risk equations to set of differential equations. In discussing the literature, we present and compare the underlying assumptions, the model specifications and the derived results. We use the previous perspectives to critically cluster the papers in the literature into a classification scheme.

Keywords: hazardous material transportation, risk assessment, minimum crash frequency, catastrophe minimization

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Introduction

The attention to HAZardous MATerials transportation (HAZMAT) research dates back 1980's, mainly due to growing safety concerns in developed countries (see, e.g., [1-18]). After a slight slow-down mainly caused by the difficulty of gathering accurate and relevant data, it has recently gained emphasis again (see, e.g., [19- 41]).

This renewed interest is also owed to two factors that have acquired more and more importance in the recent years: sustainability and equity.

Sustainability is a systemic concept that, according to World Commission on Environment and Development, relates to the continuity of economic, social, institutional and environmental aspects of human society. Hence, sustainability is the long-term compatibility between the economic and the environmental and the social dimensions of development (see, e.g., [42]).

According to [4] equity regards the public sensitivity to HAZMAT as the beneficiaries from these shipments are usually those who live near production facilities or the delivery points, yet also the populations living along HAZMAT routes are also exposed to transportation risks (see, e.g., [15];[43];[44]). This lack of burden-benefit concordance is typical source of public opposition to hazardous material shipments. The shipment of nuclear fuel, also spent, offers a good example of equity-based public opposition (see, e.g., [1]; [45]; [46]; [47]; [48]; [49]; [50]; [51]; [52];[53]).

The hazardous materials transportation requires a risk management process that involves set of crucial logistic decisions referring to, as an example, the organization of the emergency response operations. In fact, the logistical decisions on the routing of HAZMAT vehicles and the emergency response must be integrated (see, e.g., [54]).

Quantification of risk of the "en-route" hazardous materials accidents is difficult because probabilities for traffic accidents are low and those involving hazardous materials are even lower. However, as the consequences of an accident involving hazardous materials can be enormous, researchers are whetted to model the risk associated with this shipment to propose various methods to design suitable routes that present interesting trade-offs between transportation costs and accident risks.

This article is based on an idea of the first author, who is also Operations Director of S.p.A. Autovie Venete, to make an attempt to encompass both theoretical and application oriented papers from disparate areas related to the commercial transport of hazardous materials. S.p.A. Autovie Venete is an important Italian motorway concessionaire and safety is its main priority. Its operators manage HAZMAT transportation following different strategies and using different technologies to detect vehicles, to give the alarm and to properly intervene in case of accidents.

This review takes into account the framework and the method of the former article [28]. The present article develops such a work, completes it with the most recent literature and it is organized as follows. In Section 2, we introduce some important concepts about risk, the main factor that differentiate HAZMAT logistic problems from other logistic problems. We also review different models of risk assessment. In Section 3, we offer a high-level view of HAZMAT logistics literature and we propose a classification scheme. In Section 4, we cluster and discuss the papers available in the literature according to the proposed scheme and we suggest directions for future research. Finally, we draw some concluding remarks in Section 5.

1. Hazardous Materials and Risk

In this section we initially define the concept of hazardous material and point out the possible sources of risk in their transportation. Then we introduce a classification of the basic risk assessment models.

1.1. What hazardous materials are

According to the US Department of Transportation [55], a hazardous material is defined as any substance or material capable of causing harm to people, property, and the environment. There are nine major hazardous material classes:

Class 1– Explosives (dynamite, caps)
2– Gases (propane, anhydrous ammonia, chlorine, oxygen)
3– Flammable Liquids (gasoline, oil, tars, diesel, kerosene)
4– Flammable Solids (plastics, asphalt shingles)
5– Oxidizing Substances (peroxides)
6– Poisonous and infectious substances (herbicides, pesticide)
7– Radioactive materials
8– Corrosives (acids)
9– Miscellaneous (PCB's, dangerous wastes).

The en-route hazardous materials involuntary accidents have low probability: [56]; [57] estimate as a typical accident rate the value of 3.0×10^{-6} accidents/vehicle-km. Nevertheless, the potentially catastrophic impacts attributed to such incidents and the large number of hazardous shipments raises serious fears to all stakeholders involved in and affected by the HAZMAT process i.e. governmental authorities, carriers, the local societies and social groups, and shippers. Yet some risk is imposed on the population living along the major highways or railways, who are asked to assume the risk with no clear benefits to them. For this reason, if the same main route segment is selected for shipments from multiple origins, the objection of people living along this route would increase considerably. These people are likely to prefer alternate routings that would spread the risks. Public opposition to hazardous material shipments has increased in recent years, due to fears of terrorist attacks on HAZMAT vehicles.

In the event of an accident, it is important for first responders to know the nature of the hazardous materials involved. Hence, for example, vehicles transporting hazardous materials must display unified placards describing the class and the nature of the cargo. On the other hand, making HAZMAT vehicles easy to identify through placards exposes them to another kind of risk: sabotage or misuse as weapons of mass destruction or of convenience.

The possibility of accidents requires the development of integrated safety management systems to implement mitigation activities, which seek the reduction of the vulnerability, and prevention activities, which try to reduce the hazard [58]. Theoretically, risk management activities can be oriented to deal with specific and defined risk and manage it optimally. Unfortunately, reality is far too complex and resources far too scarce to deal with each risk event individually, as often one hazardous event is linked or related to one or more other hazardous events. Some events triggered others. As an example [59], urban degradation caused, e.g., by unplanned urban growth, bad construction practices, or immigration of people from the rural areas, tends to disturb the balance in the urban system, influences the interaction process between different hazards and vulnerabilities increasing vulnerability levels, and then creates new hazards factors.

1.2. Risk assessment

Risk assessment is included in risk management. The key elements of risk management are divided into two phases: the pre-disaster phase and the post-disaster phase. The pre-disaster phase includes risk identification, risk mitigation, risk transfer, and preparedness; the post-disaster phase is devoted to emergency response and rehabilitation and reconstruction. Table 1 divides the key components of disaster risk management into actions required in the pre-disaster phase and actions needed in the post-disaster period [60]). A comprehensive risk management program addresses all these components: they are an integrated, cross-sector network of institutions addressing all the above phases of risk reduction and disaster recovery. Activities that need support are policy and planning, reform of legal and regulatory frameworks, coordination mechanisms, strengthening of participating institutions, national action plans for mitigation policies, and institutional development.

Risk assessments are an essential part of the process of integrating natural disaster programs with overall development objectives. These assessments identify sources of risk, vulnerable groups, and potential interventions. Risk assessment allows policymakers to specifically define the objectives of the risk management programs and to establish vulnerability reduction targets.

In the context of HAZMAT transportation, risk is characterized by two aspects: occurrence probability of an event and consequences of an occurring event. According to Alp [61], "risk is a measure of the probability and severity of harm to an exposed receptor due to potential undesired events involving a HAZMAT whereas the exposed receptor can be a person, the environment, or properties in the vicinity". The undesired events are the accidents that could lead to a release of a HAZMAT. Risk assessment connotes a systematic approach to organizing and analyzing scientific knowledge and information for potentially hazardous activities or for substances that might pose risks under specified circumstances [62]. Risk assessment can be qualitative or quantitative. Qualitative risk assessment regards the identification of possible accident scenarios and attempts to estimate the undesirable consequences (see, e.g., [63]). Quantitative Risk Assessment (QRA) tries to assess the risk in terms of the value of some indicators to be used to actively manage risk, to identify and prioritize technology needs and decision making and, finally, to evaluate regulatory alternatives (see, e.g., [64]; [65]).

Table 1. Key Elements of Risk Management

Pre-disaster phase				Post-disaster phase	
Risk identification	Mitigation	Risk transfer	Preparedness	Emergency response	Rehabilitation and reconstruction
Hazard assessment (frequency, magnitude, and location)	Physical/ structural mitigation works	Insurance and reinsurance of public infrastructure and private assets	Early warning systems and communication systems	Humanitarian assistance	Rehabilitation and reconstruction of damaged critical infrastructure
Vulnerability assessment (population and assets exposed)	Land-use planning and building codes	Financial market instruments (catastrophe bonds and weather indexed hedge funds)	Contingency Planning (utility companies and public services)	Clean-up, temporary repairs, and restoration of services	Macroeconomic and budget management (stabilization and protection of social expenditures)
Risk assessment (a function of hazard and vulnerability)	Economic incentives for promitiga-tion behavior	Privatization of public services with safety regulation (energy, water, and transportation)	Networks of emergency responders (local and national)	Damage assessment	Revitalization for affected sectors (exports, tourism, and agriculture)
Hazard monitoring and forecasting (GIS, mapping, and scenario building)	Education, training and awareness about risks and prevention	Calamity Funds (national or local level)	Shelter facilities and evacuation plans	Mobilization of Recovery resources (public, multilateral, and insurance)	Incorporation of disaster mitigation components in reconstruction activities

[66] define risk on the basis of historical data, that is, as:

$$Risks = \frac{Events}{Exposure} \tag{1}$$

where Exposure is an exposure measure, such as truck miles, and Events is the weighted number of releases or vehicular accidents. Here, the weight associated to an event expresses the level of its severity. The strength of indicators as (1) is that they represent an integrated comprehensive measure of both frequency and severity of the past undesired events, and for this reason they are frequently used in literature to assess the risk. On the other hand, the subjectivity, in defining the value of the weights that account for the severity of the events, is an unavoidable weakness of these indicators. In addition, such indicators may be not suitable to assess the risk of potential future occurrences, in presence, e.g., of technological advances. Different studies try to overcome this latter limitation (see, e.g., [67]; [68]; [69]).

As these studies are usually focused on releases that occur on the road or, in a lesser extent, along railways, they assesses the risk by taking into consideration different factors such as population density, facility type, material to be shipped and exposure. The challenge is to convert these factors into quantitative values that allow to express the probability of a hazardous materials accident and a measure of the associated consequences (e.g. expected population exposure) to apply to the links of the road (rail) network so that the best (safest) routes can be determined.

QRA involves the following key steps: (1) hazard and exposed receptor identification; (2) frequency analysis; and (3) consequence modeling. In addition, examination of risks on different types of exposed receptor is essential to cover different response characteristics in the risk assessment. Also, given the fact that public opposition is a function of perceived risks, perhaps more attention should be paid to quantifying and modeling of perceived risks.

Each step of QRA presents some difficulties. For example, the consequence modeling step requires as inputs the territorial distribution of the population exposed to the consequences of an accident. Differently, many past studies roughly assumed uniform population density along transport links.

1.2.1. Frequency analysis

According to Ang [70], the frequency analysis involves:

1. determining the probability of an undesirable event;
2. determining the level of potential receptor exposure, given the nature of the event;
3. estimating the degree of severity, given the level of exposure.

Each stage of this assessment requires the calculation of a probability distribution. As an example [71], for each unit road segment, determine the joint probability of type of accident, release, incident, and consequence as follows. Let *A* be the accident event that involves an HAZMAT carrier, *M* the release event, and *I* the incident event; finally, let *D* be indicate the type of damage to an individual. Then, using Bayes' theorem, we obtain the probability of an injury resulting from an accident related to the HAZMAT is:

$$p(A,M,I,D) = p(D|A.M,I)p(I|A,M)p(M|A)p(A) \tag{2}$$

where $p(.)$ denotes the probability of the event and $p(.|.)$ the associated conditional probability.

If S_{lm} denote the number of shipments of HAZMAT *m* on road segment *l* per year, then the product $S_{lm} \cdot p_l(A, M_m, I, D)$ corresponds to the frequency of the occurrence of the hazardous release event with consequence *D* for a person in the neighbourhood of road segment *l*.

In assessing the risk, the literature makes a distinction individual and societal risk. Such a distinction is justified as, if few people are present around the hazardous activity, the societal risk may be close to zero, whereas the individual risk may be quite high.

- Individual Risk: [72] defines the individual risk as the yearly death frequency for an average individual at a certain distance from the impact area. The analytical expressions for individual risk are often mathematically complex and their value can only determined numerically. As an example, [73] and [74] propose a model that requires the following high level variables to assess the individual risk: 1) frequency of release, 2) probability of final outcome given a release, 3) wind probability, and 4) vulnerability. Then the individual risk is expressed as

$$\text{Individual Risk } = \sum_j f_{rel}(l,v,j) \int_L Risk_{unit} \tag{3}$$

Being

$$Risk_{unit} = \sum_i p^{out}(i) \sum_k \int_o^{2\pi} p_{wind}(j,k,\theta) \cdot V(i,k,\theta) \tag{4}$$

where *frel* (l,v,j) is the release frequency for link l, vehicle typology v in season j; $p^{out}(i)$ is the probability of final outcome i given a release; p_{wind} (j,k,θ) is the probability for meteorology condition k, season j, wind direction θ; $V(i,k,\theta)$ is the vulnerability for outcome i, meteorology condition k, wind direction θ. Note the correspondence between $f_{rel}(l,v,j)$ in (*3*) and the previously introduced product $S_{lm} \cdot p_l(A, M_m, I, D)$ by [28].

- Societal Risk: R_{lm} on road segment l of hazmat m is usually defined (see, e.g., [13]; [75]) as

$$R_{lm} = S_{lm} \iint_L p_l(D_{xy} | A, M_m, I) p_l(I, A.M_m) p_l(M_m | A) p_l(A) POP_l(x,y) \cdot dxdy \tag{5}$$

Where $p_l(D_{xy} | A, M_m, I)$ is the probability that individuals on location (x, y) in the impact area L will be dead due to the incident on a route segment l and $POP_l(x, y)$ is the population density on location in the neighborhood of road segment l. By assuming that each individual in the affected population will incur the same risk, R_{lm} can be simply expressed as

$$R_{lm} = S_{lm} p_l(D | A, M_m, I) p_l(I | A, M_m) p_l(M_m | A) p_l(A) POP_l \tag{6}$$

An alternative way to describe the societal risk is the use of the so-called *FN*-curves, (see, e.g., [76] and [77]), where F is the cumulative frequency of an accident with N or more either fatalities or evacuated people. Such *FN*-curve are drawn by computing, the probability that a group of more than N persons would be impacted due to an HAZAMAT accident, for each (reasonable) value of N [78].

Expressions from (2) to (6) allow to assess the risk in the assumption that just one type of accident may happen. However, more than one type of accident, release, incident, and consequence can occur during the HAZMAT transport activity. For example, a release of flammable liquid can lead to a variety of incidents such as a spill, a fire, or an explosion. To accommodate this, [28] suggest assessing the risk as follows. Let A, M, I, and C denote respectively the set of possible accidents, releases, incidents, and consequences that may occur on road segment l. Suppose that all consequences (injuries and fatalities, property damage, and environmental damage) can be expressed in monetary terms. Then, the hazardous materials transport risk associated with road segment l can be expressed as

$$R_l = \sum_{a \in A} \sum_{m \in M} \sum_{i \in I} \sum_{c \in C} S_{lm} \cdot p_i(A_a, M_m, I_i, C_c) \cdot CONS_c \tag{7}$$

Where, $CONS_c$ is the possible c-type consequence.

In practice, researchers frequently neglect conditional probabilities and simplify the analysis by considering the expected loss (or the worst-case loss) as the measure of risk. The expected value is calculated as the product of the probability of a release accident and the consequence of the incident [79]. Hence the HAZMAT risk associated with a road segment l is expressed as

$$R_l = \sum_{m \in M} S_{lm} \cdot p(M_m) \cdot c_{lm} \tag{8}$$

where, c_{lm} is the undesirable consequence due to the release of hazmat m on road segment l. This risk model is sometimes referred to as *the technical risk* [71].

2.2.2 Security

The risk assessment methodologies introduced in the previous section may need reviewing in the next future due to the new concern for security in HAZMAT transportation. The terrorist attacks in the USA in 2001 have focused attention on what other targets terrorists may choose. It was quickly recognized that HAZMAT vehicles could be desirable targets for terrorists, and certain HAZMAT vehicles were designated as *weapons of mass destruction*, see [80]; [81]. Such concerns changed the way the HAZMAT industry operates. For example, the US Federal Government now requires HAZMAT truckers to submit to fingerprinting and criminal background checks [82].

The security issue, however, has not yet received much attention from the operations research (OR) literature. However, there is potential for OR studies, for example as below indicated.

- **Rerouting around major cities** - The risk of terrorist attacks made it very undesirable to route HAZMAT vehicles (particularly trains) through major population centres. In particular, [83] show that significant risk reductions are possible through rerouting, and [84] develop new methodology for routing with a catastrophe-avoidance objective.

- **Changes in the modeling of incidence risks** - The traditional risk assessment for HAZMAT assumes incidents are caused by traffic accidents or human error. We now know that there is a nonzero probability of a terrorist attack or a hijack. This fact increases the incident probabilities and requires a new way of modeling consequences since the impact may no longer be limited to the planned route. Furthermore, attack probabilities are unlikely to be uniform. For example, a tunnel, a bridge, or trophy buildings are likely to have higher attack probabilities than a remote and unpopulated area. In contrast, sparsely populated areas may be associated with a higher hijack probability. A hijacked vehicle's future route is unpredictable and special precautions may have to be taken to prevent it from having an incident in a densely populated area. As a result, traditional risk assessment-based route planning is no longer adequate. There are few papers on these subjects, but see [85] for probabilistic modeling of terrorist threats, and [86] and [40] for incorporation of security concerns in route planning.
- **Changes in route planning methodology** - Past HAZMAT routing literature focuses on finding a minimum risk route. Unfortunately, the use of quantitative measures and selecting routes accordingly make the routes predictable by terrorists. To minimize the probability of a successful terrorist attack or hijacking, shippers should use alternative routes. A game theory approach can be applied determine the best way of either alternating the routes or switching from one to other ones en-route time to minimize predictability. In this context, video surveillance, global positioning systems and communication equipment installed on all HAZMAT vehicles allow the precise tracking of vehicles, but also allow the implementation of such real-time decision making (see, e.g., [82]; [87]).

2. HAZMAT logistics literature

The book chapter [28] offers a relatively comprehensive of the literature up to 2005 on risk assessment, location, and routing.

2.1. Special issues of journals

Hazmat logistics has been a very active research area during the last twenty years.

- Management Science Management Science published a special issue on Risk Analysis in 1984 (Vol.30, No.4) where five papers dealt with HAZMATs and hazardous facilities. This issue was followed by a number of special issues of refereed academic journals that focus on HAZMAT transportation or location problems.
- Transportation Research Record published two special issues on HAZMAT transportation in 1988 (No.1193) that included four papers and 1989 (No.1245) that included six papers.

- Transportation Science devoted an issue to HAZMAT logistics in 1991 (Vol.25, No. 2) that contained six papers.
- Journal of Transportation Engineering published a special section on HAZMAT transportation in the March/April 1993 issue that included four papers.
- INFOR published a special double-issue on hazardous materials logistics in 1995 (Vol.33, No.1 and 2) with nine papers.
- Location Science published four papers included in a special issue dealing with HAZMATs in 1995 (Vol.3, No.3).
- Transportation Science produced a second special issue with seven papers on HAZMAT logistics in 1997 (Vol.31, No.3).
- Studies in Locational Analysis published a special issue on undesirable facility location in April 1999 (Vol.12) that contained seven papers.
- Computers & Operations Research have published a HAZMAT logistics special issue in 2007 which contains results of the most recent research in the area in 13 papers.

2.2. Books

The following books are a good starting point for those who wish to familiarize with the terminology and the problem context.

1. *Transportation of Hazardous Materials* (1993) - This book, edited by L. N. Moses and D. Lindstrom, Kluwer Academic Publishers, issues in Law, Social Science, and Engineering. It contains 18 articles presented at HAZMAT Transport '91, a national conference held at Northwestern University on all aspects of HAZMAT transport. While only a few of the articles use OR models and techniques, the book offers a multi-dimensional treatment of the subject and it is good reading for new researchers in the area.
2. *Institute for Risk Research*, University of Waterloo (1992) - Three books were produced by this Institute as a result of the First International Consensus Conference on the Risks of Transporting hazardous materials, held in Toronto, Canada in April, 1992.
3. *Transportation of hazardous materials: Assessing the Risks* (1993) - This book, edited by F.F. Saccomanno and K. Cassidy, contains 30 articles which are organized into five main chapters: Application of QRA models to the transport of hazardous materials; Analysis of hazardous materials Accident and Releases; Application of Simple Risk Assessment Methodology; Uncertainty in Risk Estimation; Risk Tolerance, Communication and Policy Implications.
4. *Comparative Assessment of Risk Model Estimates for the Transport of hazardous materials by Road and Rail* (1993) - This book, edited by F.F. Saccomanno, D. Leming, and A. Stewart, documents the assessment of a corridor exercise involving the application of several risk models to a common transport problem involving the bulk shipment of chlorine, LPG and gasoline by road and rail along predefined routes. The purpose of the corridor exercise was to provide a well defined transportation problem for analysis in order to

examine the sources of variability in the risk estimates. Seven agencies in six countries participated in this exercise.

5. *What is the Risk* (1993) - This book, edited by F.F. Saccomanno, D. Leming, and A. Stewart, book documents the small group discussions and consensus testing process from the corridor exercise conducted as part of the international consensus conference.
6. *Hazardous materials transportation risk analysis* (1994) - This book, edited by Rhyne WR, Van Norstrand Reinhold, develops a quantitative approaches for truck and train and it explains the QRA methodologies and their application to HAZMAT transportation. It also provides an extended example of a QRA for bulk transport of chlorine by truck and train. This detailed example explores every step of the QRA from preliminary hazards analysis to risk reduction alternatives. This book is a valuable reference for HAZMAT transportation risks, and it is intended for practitioners. It is not an OR book, but it provides useful information for OR research in HAZMAT transportation modeling and analysis.
7. *Guidelines for chemical transportation risk analysis* (1995) - This book, edited by American Institute of Chemical Engineers, Center for Chemical Process Safety (CCPS) New York, completes two other books in the series of process safety guidelines books produced by CCPS: Guidelines for Chemical Process Quantitative Risk Analysis (CPQRA, 1989) and Guidelines for Hazard Evaluation Procedures (HEP, 2nd edition, 1992). It is intended to be used as a companion volume to the CPQRA and HEP Guidelines when dealing with a quantitative transportation risk analysis (TRA) methodology. This book offers a basic approach to TRA for different transport modes (pipelines, rail, road, barge, water, and intermodal containers). It can be useful to an engineer or manager in identifying cost effective ways to manage and reduce the risk of a HAZMAT transportation operation.
8. *Quantitative Risk Assessment of Hazardous Materials Transport Systems* (1996) - This book, edited by M. Nicolet-Monnier and A.V. Gheorge, Kluwer Academic Publishers, contains a comprehensive treatment of the analysis and assessment of transport risks due to HAZMAT transport on roads, rail, by ship, and pipeline. It contains European case studies as well as a discussion of computer-based decision support system for HAZMAT transport problems. It is a useful reference book in the area.

2.3. Classification

The rest of this chapter deals mainly with the academic literature consisting of refereed journal articles. The number of papers published between 1982 and 2007s in this area of research has peaked in mid 1990s and has declined somewhat since 2004.

In 2007 there is again a grow-up of the importance of the matter and of the number of articles. Given the large number of papers in these last twenty years, the articles deal with different aspects of the problem and can be classified as summarized in Tab.2

Table 2. Main subjects in HAZMAT transportations literature

1. Risk assessment	3. Combined facility location and routing
2. Routing	4. Network design

According to [28], we believe in a simple classification that can be useful in providing some structure to the rest of the chapter. One possible classification is the following (in no particular order):

C: with security consideration; DSS: Decision Support System model; G: using GIS; M: Multiobjective; S: Stochastic; T: Time-varying; U: Survey/Annotated Bibliography

Table 3 - A Classification of Hazmat Transportation Models

Risk assessment	Road	Jonkman, et al. (2003), Nardini et al. (2003), Martinez-Alegria et al. (2003)[G,] Rosmuller and Van Gelder (2003), Abkowitz (2002)[C], Fabiano et al. (2002), Kimberly and Killmer (2002), Saccomanno and Haastrup (2002)[tunnels], Hollister (2002), Hwang et al. (2001), Abkowitz et al. (2001), Verter and Kara (2001)[G], Efroymson and Murphy (2000), ICF Consulting (2000), Leonelli et al. (1999), Zhang et al. (2000)[G], Pet-Armacost et al. (1999), Cassini (1998), Mills and Neuhauser (1998), Cutter and Ji (1997), Groothuis and Miller (1997), Lovett et al. (1997)[G], Pine and Marx (1997), Alp and Zelensky (1996), Ertugrul (1995), Sissell (1995), Chakraborty and Armstrong (1995), Erkut and Verter (1995a)[U], Erkut and Verter (1995b), Moore et al. (1995), Spadoni et al. (1995), Verter and Erkut (1995)[U], Gregory and Lichtenstein (1994), Macgregor et al. (1994), Hobeika and Kim (1993), Sandquist et al. (1993), Harwood et al. (1993), Abkowitz et al. (1992), Glickman (1991), Grenney, et al. (1990)[DSS], Kunreuther and Easterling (1990), Chow et al. (1990), Abkowitz and Cheng (1989), Ang and Briscoe (1989), Harwood et al. (1989), Abkowitz and Cheng (1988), Hillsman (1988), Horman (1987), Keeney and Winkler (1985), Scanlon and Cantilli (1985), Pijawka et al. (1985), Kunreuther, et al. (1984), Philipson et al. (1983), Keeney (1980), Shappert et al. (1973)
	Rail	Anderson and Barkan (2004), Barkan et al. (2003), Fronczak (2001), Orr et al. (2001), Dennis (1996), Larson (1996), Glickman and Golding (1991), McNeil and Oh (1991), Saccomanno and El-Hage (1991), Saccomanno and El-Hage (1989), Glickman and Rosenfield (1984), Glickman (1983),
	Marine	Douligeris, et al. (1997), Roeleven et al. (1995), Romer et al. (1995)
	Air	LaFrance-Linden et al. (2001)

	Road + Rail	Brown and Dunn (2007), Milazzo et al. (2002), Bubbico et al. (2000), Neill and Neill (2000), Deng et al. (1996), Leeming and Saccomanno (1994), Purdy (1993), Saccomanno, and Shortreed (1993), Saccomanno, et al. (1989), Vanaerde et al. (1989), Glickman (1988), Swoveland (1987)	
	Road + Rail + Marine	Andersson (1994)	
	Road + Rail + Marine + Air	Kloeber et al. (1979)	
Routing	Local Routing	Road	Akgün et al. (2007), Duque et al. (2007), Erkut and Ingolfsson (2005), Huang and Cheu (2004)[C], G, Huang et al. (2003)[C], M, Kara et al.(2003), Luedtke and White (2002)[C], Paté-Cornell (2002), Marianov et al. (2002), Frank et al. (2000), Erkut and Ingolfsson (2000), Leonelli et.al. (2000), Zografos et al. (2000)[DSS], Erkut and Verter (1998), Tayi et al. (1999)[M], Bonvicini et al. (1998), Marianov and ReVelle (1998)[M], Verter and Erkut (1997), Sherali et al. (1997)[M], Nembhard and White (1997)[M], Erkut and Glickman (1997), Jin and Batta (1997), Verter and Erkut (1997), Erkut (1996), Jin et al. (1996), Ashtakala and Eno (1996)S, Beroggi and Wallace (1995), Boffey and Karkazis (1995), Erkut (1995), Moore et al. (1995), Karkazis and Boffey (1995), Glickman and Sontag (1995)[M], McCord and Leu (1995)[M], Sivakumar et al. (1995), Beroggi (1994), Beroggi and Wallace (1994), Ferrada and Michelhaugh (1994), Patel and Horowitz (1994)G, Lassarre et al. (1993)[G], Sivakumar et al. (1993), Turnquist (1993)[M], S, Wijeratne et al. (1993)[M], Lepofsky et al. (1993)[G], Beroggi and Wallace (1991), Miaou and Chin (1991), Gopalan et al. (1990a), Chin and Cheng (1989)[)M], Zografos and Davis (1989)[M], Abkowitz and Cheng (1988)[M], Batta and Chiu (1988), Vansteen (1987), Cox, and Turnquist (1986), Belardo et al. (1985), Saccomanno and Chan (1985), Urbanek and Barber (1980), Kalelkar and Brinks (1978)[M]
		Rail	Verma and Verter (2005), McClure et al. (1988), Coleman (1984), Glickman (1983)
		Marine	Iakovou (2001), Li et al. (1996), Haas and Kichner (1987)

		Road + Rail	Glickman (1988)
		Road + Rail + Marine	Weigkricht and Fedra (1995) [DSS]
	Local Routing and Scheduling (on Road)	Zografos and Androutsopoulos (2004)[M], Zografos and Androutsopoulos (2002)[M], Miller-Hooks and Mahmassani (2000)[S,T], Bowler and Mahmassani, (1998)[T], Miller-Hooks and Mahmassani (1998)[S,T], Sulijoadikusumo and Nozick (1998)[M,T], Nozick et al. (1997)[M,T,] Smith (1987)[M], Cox and Turnquist (1986)	
	Global Routing	Road	Carotenuto et al. (2007a,b), Dell'Olmo et al. (2005), Akgün et al. (2000), Marianov and ReVelle (1998), Lindner-Dutton et al. (1991), Gopalan et al. (1990a, b), Zografos and Davis (1989)
		Marine	Iakovou et al. (1999)
Combined facility location and routing	Alumur and Kara (2007), Cappanera et al. (2004), Berman et el. (2000), Giannikos (1998)[M], Helander and Melachrinoudis (1997), List and Turnquist (1998), Current and Ratick (1995)[M], Jacobs and Warmerdam (1994), Boffey and Karkazis (1993), Stowers and Palekar (1993), List and Mirchandani (1991)[M], List, et al. (1991)[U], Revelle et al. (1991), Zografos and Samara (1989), Peirce and Davidson (1982), Shobrys (1981)		
Network design	Erkut and Alp (2007a,b), Berman et al. (2007), Erkut and Gzara (2005), Verter and Kara (2005), Kara and Verter (2004)		

Although we have offered this simple classification, it is fair to say that numerous papers deal with problems that lie at the intersection of the above areas and such problems are receiving increasingly more attention in the literature. Table 3 suggests that the HAZMAT transportation problems on highways received the most attention from the operations researchers. In contrast, HAZMAT transportation via air or pipeline, as well as intermodal HAZMAT transportation has received almost no attention.

3. Literary review of problems and models

In Table 2, we suggest a schematic classification of the academic literature of HAZMAT that now we review. Rather than giving a detailed separate presentation of each work, we outline the most relevant guidelines emerging from the literature. We consider separately risk assessment and routing, combined facility location and network design.

3.1. Risk Assessment

Risk is defined as a measure of human injury, environmental damage, or economic loss in terms of both the incident likelihood and the magnitude of the loss or injury [88]. Risk is an integral part of the hazardous materials transportation literature. The majority of articles are operations research studies for minimizing risk on a transport route. The risk equations in the OR studies tend to be relatively simple and are often variations on the release probability or the product of release probability and consequences. Other articles focus on calculating risk as part of QRA studies [23]. These latter articles are typically written by environmental, civil, and chemical engineers who incorporate demographic, meteorological, and chemical databases in calculating risk. These OR and QRA studies are focused on releases that occur on the road or along railways. There is not a focus on transport-support activities, such as loading or unloading of containers. Although there are differences in the accident scenarios surrounding these two activities, many of the variables and associations and hence the general Bayesian network structures are the same.

The great majority of existing studies attempt to minimize or calculate the risk of potential future occurrences. The HAZMAT literature does not seem interested in modeling the past release incidents to determine the influence of the relevant variables. One notable exception is a study by [89] in which various sociological, behavioural, and perceptual variables affect the impact of an HAZAMAT release, was depicted using an influence diagram. From this perspective, the decision model suggested by Burns and Clemen is unique within the HAZMAT transport literature by virtue of its exploratory, statistical nature. In general, this literature lacks a focus on data-driven analysis of outcomes relative to the influencing variables.

A possible reason of this lack is owed to the fact that past data are not very reliable. Using general truck accident data for HAZMAT trucks overestimates the accident probabilities. What makes matters worse is that there is no agreement on general truck accident probabilities and conflicting numbers are reported by different researchers. Furthermore, applying national data uniformly on all road segments of similar type is quite problematic since it ignores hot spots such as road intersections, highway ramps, and bridges. Researchers need to have access to high quality accident probability data and empirical or theoretical research that leads to improvements in the quality of such data should be welcome. [23] describe a quantitative risk assessment approach for hazardous materials transportation that employs considerable statistical data from past incidents. They illustrate application of this method to evaluating distances to which the public should be protected immediately following an accidental release of toxic materials that pose an inhalation hazard. While this paper focuses on emergency response aspects of the problem, the framework that they describe has applications to societal risk estimation and routing optimization for a wide variety of hazardous materials.

Typically, accident and release probabilities have been estimated for a given road and area type using averaged values, which have limited sensitivity in specific situations (see, e.g., [90]). Differently, some recent empirical works suggest the use of fuzzy logic to determine the accident frequency (see, e.g., [91]). Additional exploratory work on accident probabilities is still needed. There is a lack of agreement on how HAZMAT transport risk should be represented [71].

Risk is described at least from seven different perspectives:

- Accident or Release Probability [92]
  - Probability of a vehicular accident of the HAZMAT truck [93]
  - Probability of a vehicular accident that leads to release [94]
  - Probability of a release [71]

- Consequences [95]
- Consequence Probability
  - Individual Risk [96]
  - Societal Risk [71]
- Numerical Indices [88].
- Exposure and Product of Exposure [97]
- Expected Value [41]
- Variations on Expected Value [74]

However, as already described in Section 2.2 risk is usually assessed in terms of the following high-level variables: 1) accident or release probability, 2) consequence level, 3) population count, and 4) exposure amount, such as amount of HAZMAT transported.

Several authors whose risk equations are limited to these high level variables characterize their risk models as simple (see e.g. [98]; [44]. More complex formulations [19] for risk assessment include the above high-level variables along with variables such as 5) wind probability or 6) fatality probability, also known as vulnerability. In turn, the latter variables are often specified in terms of sub-variables, or input parameters [99]. However, the numerical relationships of the sub-variables to the higher level variables or outcomes are not provided to the reader and are therefore not a discussion focus [73]. For example, [74] suggest that the release probability calls for the use of vehicle type and material type as sub-variables. However, they neither discuss nor provide in the article the exact numerical relationship of vehicle type or material type to release probability.

3.2. Route Optimization for Hazardous Materials Transport

In the following we briefly introduce some of the most relevant work dealing with route optimization for HAZMAT.

[95] focus on the damage induced to the population in case of an accident. In this research study attention is given to the dispersion of the HAZMAT through air. Therefore, the impact area is not defined by a given bandwidth, but is a function dependent on the type of material transported and the meteorological conditions at the moment of the accident.

[100] made research study that has considered a simplified approach to quantify risk. This research study focuses in the development of a spatial decision support system for the selection of route for the transport of HAZMAT within the United States of America. The element at risk considered is the population located in the impact area of the possible accident. The impact area is located alongside the route and it extents to both sides of the route up to a predefined bandwidth.

[74] introduce a methodology based on the quantification of individual and societal risk indexes for the selection of optimal route for the transport of HAZMAT. The hazard considered is the accident probability of a HAZMAT transport unit, and the population is considered as the element at risk, being affected in the case of an accident. The population value results from aggregating the population travelling on the transport network and the population located adjacent to the transport network. In a previous article [73] mention that the use of individual and societal risk can give an accurate

indication of risk, however to calculate these values, a great amount of data and programming effort is required. Due to this, a number of other simplified risk quantification techniques have been adopted in other research studies some of these are mentioned above.

[41] consider the population as the element at risk. In this study the population located inside the impact area is assumed to have the same vulnerability value, namely one. The risk for the population is then defined as the product of the individual risk and the total population. Individual risk is assessed only on hazards, vulnerability, and element at risk. The previous results could be generalized assessing the individual risk on the basis of also the accident probability of a HAZMAT transport unit, and the population is considered as the element at risk, being affected in the case of an accident as proposed by [73].

[101] describe a method for finding nondominated paths for multiple routing objectives in networks where the routing attributes are uncertain, and the probability distributions that describe those attributes vary by the time of day. This problem is particularly important in routing and scheduling of shipments of very hazardous materials. The method developed extends and integrates the work of several previous authors, resulting in a new algorithm that propagates means and variances of the uncertain attributes along paths and compares partial paths that arrive at a given node within a user-specified time window. The comparison uses an approximate stochastic dominance criterion.

[102] study the problem of determining a path for a shipment of hazardous materials between a pre-specified origin-destination pair on the plane taking into account minimization of risks during the transportation and cost of the path. Given a source point *a*, a destination point *b*, a set *S* of demand sites (points in the plane) and a positive value *I*, the authors want to compute a path connecting *a* and *b* with length at most *I* such that the minimum distance to the points in *S* is maximized. They propose an approximate algorithm based on the bisection method to solve this problem and the technique reduces the optimization problem to a decision problem, where one needs to compute the shortest path such that the minimum distance to the demand points is not smaller that a certain amount *r*. To solve the decision task, Diaz-Banez, Gomez and Toussaint transform the problem to the computation of the shortest path avoiding obstacles. This approach provides efficient algorithms to compute shortest obnoxious paths under several kinds of distances.

[35] study the determination of optimal routes for hazardous material transportation trying to find trade-off solutions among many conflicting objectives in the analysis, such as travel cost, population exposure and environmental risk or security concerns. The authors use as generalized objective the product of the different objective functions and solve a complex shortest path problem that often present several “efficient" solutions. A case study with 8 objective functions has been carried out on a road network in Singapore. A geographical information system is used to quantify road link attributes, which are assumed linear and deterministic for the sake of simplicity. The proposed algorithm derives four significantly different routes, which conform to intuition.

[36] propose a novel vehicle routing and scheduling problem in transporting hazardous materials for networks with multiple time-varying attributes. It actually aims to identify all nondominated time-varying paths with fixed departure times at the origin and fixed waiting times at intermediate nodes of the paths for each given pair of origin and destination. Three kinds of practical constraints must also respected: limited

operational time period, limited service time, and limited waiting time window at each node. Based on the assumption of linear waiting attributes at a node, the proposed problem can be transformed into a static multiobjective shortest path problem in an acyclic network reconstructed by the space-time network technique. An efficient dynamic programming method is then developed.

[103] analyzes the possible use of telegeomonitoring in HAZMAT transportation. The author proposes a telegeomonitoring system that uses a geographic information system to represent civil infrastructure (urban network, land use, industries, etc.) and a decision support systems technology to asses the risk and to evaluate the K-best paths that minimize transportation risk. To this end, routing algorithms on graphs are extended to deal with fuzzy risk; in particular, the K-best fuzzy shortest paths.

[104] proposes a model of flow propagation, assuming "packets" of vehicles and uniformly accelerated movement. Such an approach allows the author to propose a mesoscopic model of the HAZMAT vehicles movements that appears lifelike in the representation of outflow dynamics and easy polinomiale to solve.

[31] study the problem of routing hazardous material on a multimodal network with time-varying link travel times and intermodal options. The problem is formulated as a Dynamic Program and an intermodal/multimodal shortest path algorithm is modified to compute minimum risk paths by combining the available transport modes, while accounting for transfer delays and transportation costs. The algorithm is implemented on a test network to observe changes in the solution under different scenarios. Computational performance is evaluated on networks of different sizes and the algorithm's efficient running time makes it appropriate for use on realistic networks for both planning and real-time operations.

[19] focus on the effects of weather systems on HAZMAT routing. They start by analyzing the effects of a weather system on a vehicle traversing a single link. This helps characterize the time-dependent attributes of a link due to movement of the weather systems. This analysis is used as a building block for the problem of finding a least risk path for HAZMAT transportation on a network exposed to weather changes. Several methods are offered to solve the underlying problem, and computational results are reported. Two conclusions are drawn from this paper: (1) it is possible to determine the time-dependent attributes for links on a network provided that some assumptions on the nature of the weather system are made; (2) heuristics can provide effective solutions for practical size problems while allowing for parking the vehicle to avoid weather system effects; technologies (4) how to route waste residues to disposal centres. The model has the objective of minimizing both the total cost and the transportation risk.

[20] propose a new multiobjective location-routing model that is object of a large-scale implementation in the Central Anatolian region of Turkey. The aim of the proposed model is to answer to the following questions: (1) where to open treatment centres and with which technologies, (2) where to open disposal centres, (3) how to route different types of hazardous waste to which of the compatible treatment technologies (4) how to route waste residues to disposal centres. The model has the objective of minimizing both the total cost and the transportation risk. The model proposed is manageable for a realistic problem in the Central Anatolian region of Turkey. Given that the hazardous waste management problem is a strategic one that will be solved infrequently, the authors believe that the computational effort is reasonable for problems with up to 20 candidate sites and that the application is a few orders of magnitude better than other applications in the literature. Most of the papers

present applications for small problems such as with 10 or 15 generation nodes and with 3 or 4 candidate sites, whereas Alumur and Kara applied their model with 92 generation nodes and with 15 and 20 candidate sites. As another research direction, the authors suggest that they can include other objectives of the hazardous waste management problem in their model. For example, one can maximize the energy production after the incineration process. Differently, one can minimize the risk due to the location of the treatment facility. When multiple objectives are considered, the model can be managed with different multi-objective solution techniques. Alumur and Kara propose a relatively simple multi-objective solution technique for ease of application. Apart from the different objectives, one can expand the mathematical model so that the locations of the recycling facilities and the corresponding routing strategies are also determined. Lastly, a multi-period version of the model can be used to schedule the processing of different types of waste. In this case, the compatibility constraint will gain more importance. That is, any new model should not allow wastes that are not compatible with each other to be transported or incinerated at the same time.

[22] study how undesirable consequences of hazardous materials incidents can be mitigated by quick arrival of specialized response teams at the accident site. They present a novel methodology to determine the optimal design of a specialized team network so as to maximize its ability to respond to such incidents in a region. They show that this problem can be represented via a maximal arc-covering model. They discuss two formulations for the maximal arc-covering problem, a known one and a new one. Through computational experiments, the authors establish that the known formulation has excessive computational requirements for large-scale problems, whereas the alternative model constitutes a basis for an efficient heuristic. The methodology is applied to assess the emergency response capability to transport incidents, which involve gasoline, in Quebec and Ontario. [105] point out the possibility of a significant improvement via relocation of the existing specialized teams, currently stationed at the shipment origins.

[24] study the problem of managing a set of HAZMAT requests in terms of HAZMAT shipment route selection and actual departure time definition. For each HAZMAT shipment, a set of minimum and equitable risk alternative routes from origin to destination points and a preferred departure time are given. The aim is to assign a route to each HAZMAT shipment and schedule them on the assigned routes in order to minimize the total shipment delay, while equitably spreading the risk spatially and preventing the risk induced by vehicles travelling too close to each other. This HAZMAT shipment scheduling problem is modelled as a job-shop scheduling problem with alternative routes. No-wait constraints arise in the scheduling model as well, since, supposing that no safe area is available, when a HAZMAT vehicle starts travelling from the given origin it cannot stop until it arrives at the given destination. A tabu search algorithm is proposed for the problem, which is experimentally evaluated on a set of realistic test problems over a regional area, evaluating the provided solutions also with respect to the total route risk and length.

[26] consider the problem of designating HAZMAT routes in and through a major population centre. Initially, they restrict the attention to a minimally connected network (a tree) where we can predict accurately the flows on the network. They formulate the tree design problem as an integer programming problem with an objective of minimizing the total transport risk. Such design problems of moderate size can be solved using commercial solvers. Then they develop a simple construction heuristic to expand the solution of the tree design problem by adding road segments. Such

additions provide carriers with routing choices, which usually increase risks but reduce costs. The heuristic adds paths incrementally, which allows local authorities to trade off risk and cost. Erkut and Alp use the road network of the city of Ravenna, Italy, as a case study.

[27] consider an integrated routing and scheduling problem in HAZMAT transportation when accident rates, population exposure, and link durations on the network vary with time of day. They minimize risk subject to a constraint on the total duration of the trip and allow for stopping at the nodes of the network. The authors consider four versions of this problem with increasingly more realistic constraints on driving and waiting periods, and propose pseudo-polynomial dynamic programming algorithms for each version. They use a realistic example network to experiment with theirs algorithms and provide examples of the solutions generated. The computational effort required for the algorithms is reasonable, making them good candidates for implementation in a decision-support system.

The en-route stops allow us to take full advantage of the time-varying nature of accident probabilities and exposure and result in the generation of routes that are associated with much lower levels of risk than those where no waiting is allowed.

4. Synthesis and Conclusions

4.1. Synthesis

Ethics is not a substitute for a fundamentally sound business strategy, and so it is important to provide value-added tools for companies to help them manage all aspects of sustainable and socially responsible business practices in the HAZMAT area. In general, the studies in the HAZMAT transport literature do not have an exploratory modelling focus. Rather, various analytical equations for risk are used in route optimization or quantitative risk assessment research. The lack of focus on exploratory modelling of risk in terms of its important variables presents a gap or opportunity in the HAZMAT literature.

[28] reflected on the state-of-the-art as of 2005, and pointed out a number of directions for future research. In the following two years, some of the problem areas proposed in [106][107]and in [28] were investigated by researchers, whereas many others remained relatively unexplored. From the methodological perspectives, global routing problems on stochastic time-varying networks received no attention despite their relevance and application potential.

HAZMAT transportation network design problem which considers all involved parties (government and the carriers) is a relatively young research topic. The most obvious extension of the existing models in this area is to incorporate uncertainty and consider multiple objectives as the HAZMAT transportation problems are highly stochastic in nature and involve multiple criteria (and players). There is an increase on utilizing geographic information systems either for data input or combined with optimization models to conduct more realistic risk assessment. We believe that there are still many important OR problems in HAZMAT transportation. Researchers can find additional important references in [108-266]. However, we think the focus will shift from a priori optimization toward real-time adaptive decision making for several reasons, such as the availability of the necessary technology and data, as well as security concerns. While it is rather unfortunate that terrorist attacks can and do happen, their possibility opens up a new frontier for operations researchers in general, and HAZMAT transport researchers in particular.

4.2. Conclusions

- Researchers need to have access to high quality accident probability data and empirical or theoretical research that leads to improvements in the quality of such data would be welcome.
- Applying national data uniformly on all road segments of similar type is quite problematic since it ignores hot spots such as road intersections, highway ramps, and bridges.
- There is no agreement on general truck accident probabilities and conflicting numbers are reported by different researchers.
- Given the limitation of QRA, and the fact that public opposition is a function of perceived risks, perhaps more attention should be paid to quantifying and modeling of perceived risks. We believe more work is needed to improve our understanding of how perceived risks change as a function of the hazardous substance, the distance to a hazardous activity, and the volume of the activity.
- More work is needed to improve understanding of how perceived risks change as a function of the hazardous substance, the distance to a hazardous activity, and the volume of the activity.
- Geographic information systems make it possible to use more precise population information. However, using census-based population data for daytime HAZMAT movements makes little sense since census data is residence-based and most residents are not at home during the day. Researchers need to take the next step and incorporate day versus night population distributions, as well as high-density population installations such as schools and hospitals. While this is done relatively easily for QRA of a single route, it is more complicated to generate the necessary data for an entire transportation network.

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