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Chapter 9 - HAZARDOUS MATERIALS TRANSPORTATION

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- The transportation of hazardous materials (or dangerous goods) deserves to be treated primarily due to the risks as sociated with this activity. Although the industry has an excellent safety record, accidents do happen, and the consequences can be significant, due to the nature of the cargo.
- Reduction of hazardous material (hazmat) transportation risks can be achieved in many different ways. Some of these risk reduction measures, such as driver training and regular vehicle maintenance, have little connection to modeling and operations research (OR), whereas others offer interesting challenges to OR.
- This chapter focuses on applications of OR models to hazmat transportation, providing a relatively comprehensive review of the literature.
- Figure 1 shows the distribution of accidents/incidents by hazmat class in 2003. ***An accident resulting in a release of the hazmat is called an incident***. The figure shows that flammable–combustible liquids and corrosive materials accounted for the majority of hazmat accidents/incidents in the USA (US DOT, 2004a).

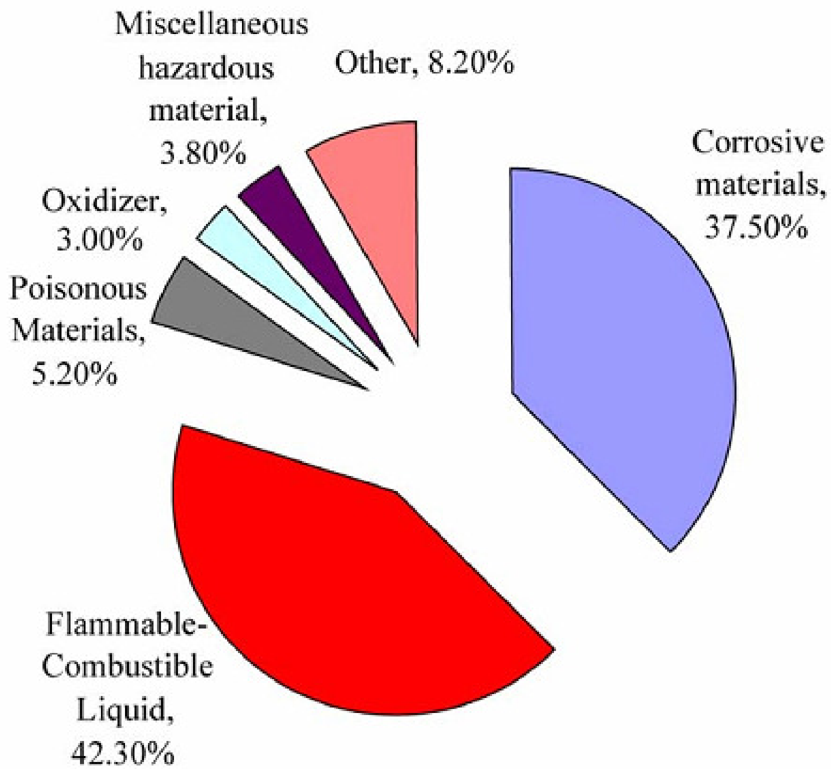

Fig. 1. Accident/incident by hazmat class in 2003 (US DOT, 2004a).

- Hazmat transport incidents can occur at the origin or destination (when loading and unloading) or en-route.
- Incidents involving hazmat cargo can lead to severe consequences characterized by fatalities, injuries, evacuation, property damage, environmental degradation, and traffic disruption.

- In 2003, there were 488 serious incidents (among a total of 15,178 incidents) resulting in 15 deaths, 17 major and 18 minor injuries, and a total property damage of $37.75 million (US DOT, 2004c). About 90% of hazmat incidents occur on highways. As far as causes go, human error seems to be the single greatest factor in all hazardous materials incidents (minor and serious incidents).
- The annual number of nonhazmat transportation accidents in the USA is estimated to be 126,880, in contrast to the approximately 15,000 hazmat transportation accidents and incidents (FMCSA, 2001).
- Table 1 contrasts the average costs (per event) of hazmat and nonhazmat motor carrier accidents and incidents for one year.
- Although the cost of an average hazmat incident is not significantly higher than the cost of a nonhazmat incident, the cost of a hazmat incident resulting in fire or explosion is significantly higher.
- **Hazmat transportation accidents are perceived as low probability–high consequence** (LPHC) events and data seem to support this perception.
- For example, chlorine leaking from damaged tank cars due to a derailment in Mississauga, Ontario in 1979, forced the evacuation of 200,000 people. In 1982, a gasoline truck explosion in a tunnel in Afghanistan caused 2700 fatalities. Most transport accidents that impact a large number of people and result in significant economic loss involve a hazmat cargo.

Table 1.
Comparative costs of hazmat and nonhazmat motor carrier accident/incident events (FMCSA, 2001)

Type of accident/incident event	Average cost (in US$)	Average traffic delay (in hours)
Nonhazmat events	340,000	2
All hazmat events	414,000	–
Hazmat events with spill/release	536,000	5
Hazmat events with fire	1,200,000	8
Hazmat events with explosion	2,100,000	12

- Hazmat transportation involves multiple players such as shippers, carriers, packaging manufacturers, freight forwarders, consignees, insurers, governments, and emergency responders; each has a different role in safely moving hazardous materials from their origins to their destinations. There are often multiple handoffs of material from one party to another during transport.
- The various parties, ranging from individuals or small firms to large multinational organizations, may have overlapping and unclear responsibilities for managing the risks (ICF Consulting, 2000). Furthermore, each party may have different priorities and viewpoints.

- Although the transportation department or local government is responsible for designating allowable routes that reduce risk, a carrier company would, in general, try to identify the route that minimizes the fuel costs and travel times, between the origin and destination for each shipment.
- Some routes have short lengths but move through heavily populated areas; some routes avoid heavily populated areas but are longer, resulting in higher transport costs and accident probabilities; while other routes use major freeways and thus minimize travel time but may be associated with higher accident rates.
- Thus, hazmat transportation is a typical multi objective problem with multiple stakeholders. Multiobjective / multistakeholder problems are complicated to solve.
- Hazmat transport problems are further complicated by public sensitivity surrounding these problems.
- The **concept of social amplification of risk** (see Kasperson et al., 1988; Renn et al., 1992) indicates that public assessment of a risk depends not only on its magnitude but also on subjective perceptions. The **individual and social perceptions of risk can be heightened or attenuated by many factors such as extensive media coverage of the hazard event** (see, e.g., Horlick-Jones, 1995), involvement of social groups (see, e.g., Moore, 1989), inaccuracies and inconsistencies in the communication process that lead to rumors and speculations on risk magnitude (see, e.g., Mileti and O’Brien, 1992; Barnes, 2001).

- The amplification of the risk of a relatively minor hazmat accident may imply much stronger public reaction and results in a call for action, such as tighter transport regulations or even the banning of hazmat shipments via a certain mode of transport, in some extreme cases.
- **Public opposition to hazmat shipments has increased in recent years, due to fears of terrorist attacks on hazmat vehicles**. Hazmats could pose a significant threat during transportation, when they are particularly vulnerable to sabotage particularly given how easy it is to identify a hazmat vehicle (as well as the specifics of their cargo) given the current system of hazmat placards. As a result some jurisdictions are trying to force a rerouting of hazmat vehicles away from populated areas by implementing local laws.
- Much of the discussion to this point also applies to the location of hazardous facilities. If anything, the risks and the public opposition are higher for fixed facilities than for transport.

High level view of hazmat logistics literature

- Hazmat logistics has been a very active research area during the last twenty years. In 1984 Management Science published a special issue on Risk Analysis (Vol. 30, No. 4) where five papers dealt with hazmats and hazardous facilities. This was followed by a number of special issues of refereed academic journals that focus on hazmat transportation or location problems.

Special journal issues

- *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.
- There was a special section on hazmat transportation in the March/April 1993 issue of the *Journal of Transportation Engineering* that included four papers.
- A special double-issue of *INFOR on hazardous materials logistics* was published in 1995 (Vol. 33, No. 1 and 2) with nine papers.
- Four papers were included in a special issue of *Location Science* dealing with hazmats in 1995 (Vol. 3, No. 3).
- *Transportation Science* produced a second special issue on hazmat logistics in 1997 (Vol. 31, No. 3) with seven papers.
- *Studies in Locational Analysis* published a special issue on undesirable facility location in April 1999 (Issue 12) that contained seven papers.
- *Computers & Operations Research* will publish a hazmat logistics special issue in 2007 which will contain results of the most recent research in the area in 13 papers.

- These special issues contain many useful papers and they offer a good starting point for research in this area. Likewise, the book chapter by Erkut and Verter (1995a) offers a relatively comprehensive survey of the literature up to 1994, and the annotated bibliography by Verter and Erkut (1995) offers a good list of pre-1994 references in risk assessment, location, and routing.
- Perhaps an even better starting point for those who wish to familiarize themselves with the terminology and the problem context are the following books.

Books

- *Transportation of Hazardous Materials: Issues in Law, Social Science, and Engineering* (1993), edited by L.N. Moses and D. Lindstrom, Kluwer Academic Publishers. This book contains 18 articles presented at Hazmat Transport '91, a national conference held at Northwestern University on all aspects of hazmat transport.
- *Transportation of DangerousGoods: Assessing the Risks* (1993), edited by F.F. Saccomanno and K. Cassidy. This book contains 30 articles which are organized into five main chapters: Application of QRA models to the transport of DangerousGoods; Analysis of Dangerous Goods Accident and Releases; Application of Simple Risk AssessmentMethodology; Uncertainty in Risk Estimation; Risk Tolerance, Communication and Policy Implications.
- *Comparative Assessment of Risk Model Estimates for the Transport of Dangerous Goods by Road and Rail* (1993), edited by F.F. Saccomanno, D. Leming, and A. Stewart. This book 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 pre defined routes.

- *What is the Risk* (1993), edited by F.F. Saccomanno, D. Leming, and A. Stewart. This book documents the small group discussions and consensus testing process from the corridor exercise conducted as part of the international consensus conference.
- *Hazardous Materials Transportation Risk Analysis: Quantitative Approaches for Truck and Train* (1994), Rhyne WR, Van Norstrand Reinhold. This book explains the quantitative risk analysis (QRA) methodologies and their application to hazmat transportation.
- *Guidelines for Chemical Transportation Risk Analysis* (1995), American Institute of Chemical Engineers, Center for Chemical Process Safety (CCPS), New York. This book 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).
- *Quantitative Risk Assessment of Hazardous Materials Transport Systems* (1996),M. Nicolet-Monnier and A.V. Gheorge, Kluwer Academic Publishers. This book 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 DSS (Decision Support System) for hazmat transport problems

Web sites

- The Office of Hazardous Materials Safety (US DOT Research and Special Programs Administration): http://hazmat.dot.gov/ .
- The Hazmat 101 Web: http://www.hazmat101.com/ .
- Hazmat Magazine: http://www.hazmatmag.com/ .
- On-line hazmat school: http://www.hazmatschool.com/ .
- NationalHazardousMaterials Route Registry: http://hazmat.fmcsa.dot/gov/ .

- United Nations Economic Commission for Europe (UNECE) – Dangerous Goods and Special Cargo: http://www.unece.org/trans/danger/danger.htm .
- The Canadian Transport Emergency Centre (CANUTEC) of the Department of Transport: http://www.tc.gc.ca/canutec/ .
- A mailing list for those interested in hazmat transport: http://groups.yahoo.com/group/DangerousGoods/ .

Software

- There exists some software which has been developed to aid the analysts or decision makers in dealing with hazmat logistics. For example, ***ALOHA*** *(Areal Locations of Hazardous Atmospheres) predicts how a hazardous gas cloud might disperse in the atmosphere* after an accidental chemical release.
- In contrast to the availability of many software packages for regular truck routing, we know of only one off-the-shelf hazmat routing package that is currently available: PC*Miler|HazMat (ALK Associates, 1994). It has features that allow transportation and logistics companies to determine routes and mileages for hauling hazardous materials

Treatment of risk

- **Risk is the primary ingredient that separates hazmat transportation problems from other transportation problems.**
- In the context of hazmat transport, ***risk is a measure of the probability and severity of harm to an exposed receptor due to potential undesired events involving a hazmat*** (Alp, 1995). The exposed receptor can be a person, the environment, or properties in the vicinity.
- The undesired event in this context is the release of a hazmat due to a transport accident. The consequence of a hazmat release can be a health effect (death, injury, or long-term effects due to exposure), property loss, an environmental effect (such as soil contamination or health impacts on flora and fauna), an evacuation of nearby population in anticipation of imminent danger, or stoppage of traffic along the impacted route.
- Risk assessment can be qualitative or quantitative.
- Qualitative risk assessment deals with the identification of possible accident scenarios and attempts to estimate the undesirable consequences. It is usually necessitated by a lack of reliable data to estimate accident probabilities and consequence measures.
- The goal is to identify events that appear to be most likely and those with the most severe consequences, and focus on them for further analysis. It may be the only option in the absence of data – for example, assessing the risks due to the location of a permanent nuclear waste repository.

- While hazmat transport analysts are known to complain about the quality of their data (we will return to this topic later in this section), they do have access to considerable historical information on accident frequencies and fairly accurate consequence models for hazmat releases in case of accidents in many developed countries.
- Quantitative risk assessment (QRA) involves the following key steps:

  (1) hazard and exposed receptor identification ;
  (2) frequency analysis; and
  (3) consequence modeling and risk calculation.
- Identification of hazard refers to identifying the potential sources of release of contaminants into the environment, the types (e.g., thermal radiation due to jet and pool fires and fireballs, explosions, flying pieces of metals or other objects due to blast waves, toxic clouds, and flame) and quantities of compounds that are emitted or released, and the potential health and safety effects associated with each substance.
- In some cases (for example, when a release of carcinogenic substances is involved), we also need to investigate the long-term health risks of a hazmat accident. Examination of risks on different types of exposed receptor is also essential to cover different response characteristics in the risk assessment.
- The language of QRA is one of frequencies and consequences, and unlike in qualitative risk analysis, QRA results in a numerical assessment of risks involved, for example, an expected number of individuals impacted per year.

FREQUENCY ANALYSIS

- The frequency analysis involves

  (a) determining the probability of an undesirable event;
  (b) determining the level of potential receptor exposure, given the nature of the event;
  (c) estimating the degree of severity, given the level of exposure

- Each stage of this assessment requires the calculation of a probability distribution, with stage (b) and (c) involving conditional distributions. Consider a unit road segment. Suppose that there is only one type of accident, release, incident, and consequence. Let ***A*** be the accident event that involves a hazmat transporter, ***M*** the release event, and ***I*** the incident event. Suppose that the consequence of the hazmat release is expressed in terms of the number of injuries. We denote the event of an injury to an individual as ***D***. Using Bayes' theorem, we obtain the probability of an injury resulting from an accident related to the hazmat as

$$
\begin{aligned}
p(A,M,I,D) &= p(D|A,M,I)\,p(A,M,I) \\
&= p(D|A,M,I)\,p(I|A,M)\,p(A,M) \\
&= p(D|A,M,I)\,p(I|A,M)\,p(M|A)\,p(A),
\end{aligned}
$$

where ***p(E)*** denotes the probability of the event ***E*** occurring on the road segment and ***p(E|F)*** the associated conditional probability.

- Furthermore, let s_{lm} denote the number of shipments of hazmat m on road segment l per year. Note that a highway transport route from the origin to the destination consists of finitely many road segments. The product $s_{lm}p_l(A,M_m, D)$ determines the frequency of the occurrence of the hazardous release event that measures the individual risk for a person in the neighborhood of road segment l.
- Usually, the individual risk is defined as the yearly death frequency for an average individual at a certain distance from the impact area (see, e.g., Mumpower, 1986; Leonelli et al., 2000). Although no universally accepted individual risk criteria exist, one tends to compare the risk of death to de minimis of 10^{-6} to 10^{-5} deaths per year (Mumpower, 1986).
- Hazmat incidents usually impact a number of individuals. Hence, we need to move from individual risk toward societal risk. The societal risk is a characteristic of the hazardous activity in combination with its populated surroundings.
- There are several ways to express societal risk. Perhaps the simplest method is to compute the expected number of impacted individuals by multiplying the probability of impact per person with the number of persons present in the impact zone.
- Hence, the societal risk (or just risk for short) on road segment l of hazmat m, R_{lm}, can be expressed as

$$R_{lm} := s_{lm} \iint_L p_l(D_{xy}|A, M_m, I)\, p_l(I|A, M_m) \times p_l(M_m|A)\, p_l(A) POP_l(x, y)\, \mathrm{dx}\, \mathrm{dy},$$

where $\boldsymbol{p_l(D_{xy}\,|A,M_m,I)}$ 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 $\boldsymbol{POP_l(x,y)}$ is the population density on location ***(x, y)*** in the neighborhood of road segment **l**. By assuming that each individual in the affected population will incur the same risk, $\boldsymbol{R_{lm}}$ can be simply expressed as

$$R_{lm} := s_{lm}\, p_l(D|A, M_m, I)\, p_l(I|A, M_m)\, p_l(M_m|A)\, p_l(A) POP_l.$$

- Thus, 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.
- While this expected consequence is a convenient measure for OR models, the risk assessment literature prefers a richer measure, namely the FN-curve which expands the point estimate of the expectation to the entire distribution.
- To produce an FN-curve, one has to compute the probability that a group of more than N persons would be impacted due to a hazmat accident, for all levels of N. The risk level is communicated by the FN-curve, a graph with the ordinate representing the cumulative frequency distribution F of the hazardous release events which result in at least N number of impacts.

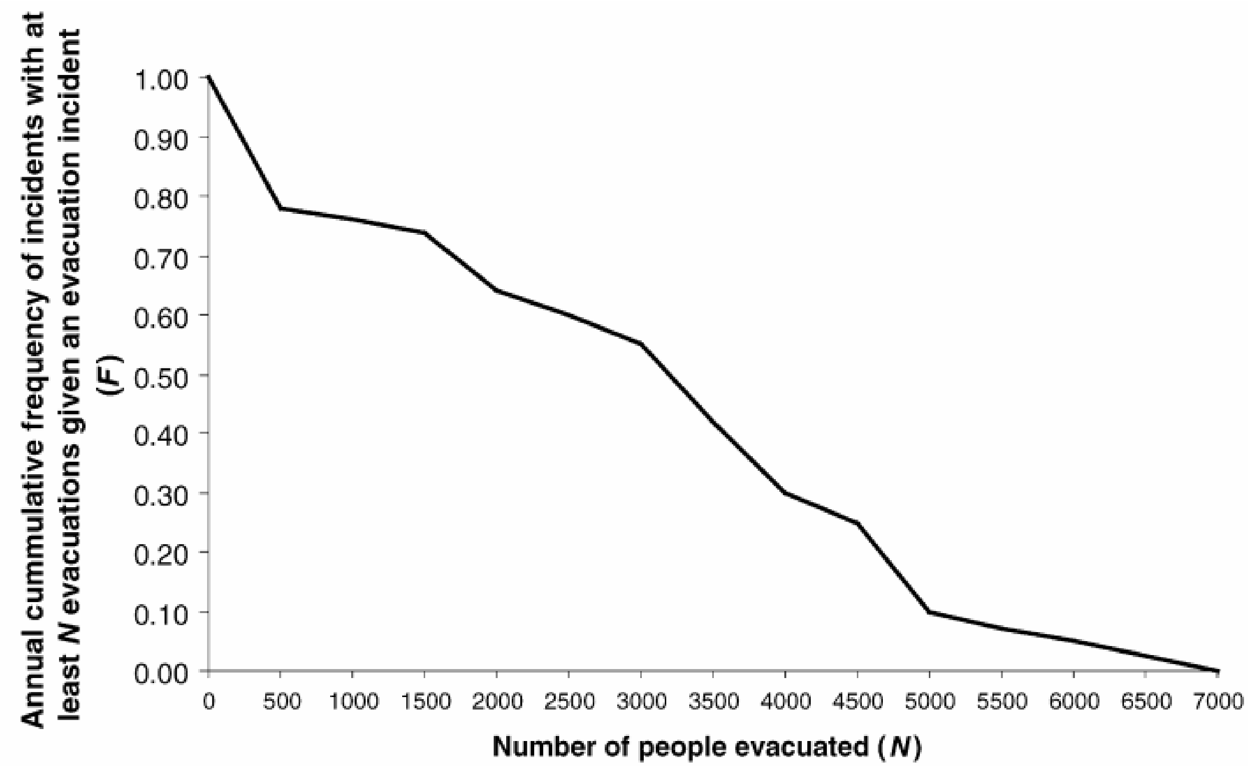

Fig. 4. A conditional *FN*-curve (given an evacuation incident).

- Clearly, 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, let ***A, M, I,*** and ***C*** denote 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 hazmat transport risk associated with road segment ***l*** can be expressed as

$$R_l := \sum_{a \in \mathcal{A}} \sum_{m \in \mathcal{M}} \sum_{i \in \mathcal{I}} \sum_{c \in \mathcal{C}} s_{lm} p_l(A_a, M_m, I_i, C_c) CONS_c,$$

  where CONSc is the possible c-type consequence.

- However, in practice, researchers frequently neglect these 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 (List et al., 1991). Hence the hazmat transport risk associated with a road segment l can be expressed as

$$R_l := \sum_{m \in \mathcal{M}} s_{lm} p(M_m) c_{lm},$$

  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***.

- As it is clear from the discussion above, *QRA depends heavily on an estimation of probabilities*. There are two primary means to estimate the accident, release, and incident probabilities:
  - historical frequencies and
  - logical diagrams (fault tree and event tree analysis).

Historical frequencies

- We can use the number of hazmat transport accidents in a given time period and the total distance traveled by hazmat trucks in the same time period to calculate the accident rate on a unit road segment (i.e., accidents per km).
- The rarity of hazmat accidents may result in insufficient information to determine whether historical figures are relevant to the circumstances of concern, particularly regarding rare catastrophic accidents.

Logical diagram-based techniques

- An alternative way to estimate the frequency (and possibly consequences) of hazmat release incidents is the use of logical diagram-based techniques, namely
  - fault tree and
  - event tree analysis.

- **Fault Tree Analysis (FTA)** is a top-down analysis tool to identify the causes of events and to quantify various accident scenarios that would cause the system fail. It starts with an identified hazard (e.g., chlorine release due to a transport accident) as the root of a tree (or top event) and works backward to determine its possible causes (e.g., collision accident, derailment, and relief valve poorly sealed) using two logical functions: OR and AND.
- FTA enables us to determine the probability of the top event on the basis of the probabilities of the basic events (e.g., **p(D | A, M, I)**, where death of an individual in hazmat transport accident is the top event) for which sufficient historical data exist or expert judgments are reliable.
- **Event Tree Analysis (ETA)**, on the other hand, is a bottom-up analysis tool. It takes at its starting point the event that can affect the system (e.g., an initial release of hazmat) and tracks them forward through sequences of interfacing system components to determine their possible consequences. It examines all possible responses to the initiating event, such as the functioning, failure, or partial failure of subsystems or different systems, in a tree structure with the branches developing from left to right.
- Each outcome of the branches is usually binary (i.e., the outcome occurs or does not occur). By assigning a probability to each branch, the probabilities of every possible outcome following the initiating event can be determined. ETA can be used in conjunction with FTA, called FETA, to identify and quantify the possible consequences of the top event in fault tree.
- Figure shows a fault tree in conjunction with an event tree.

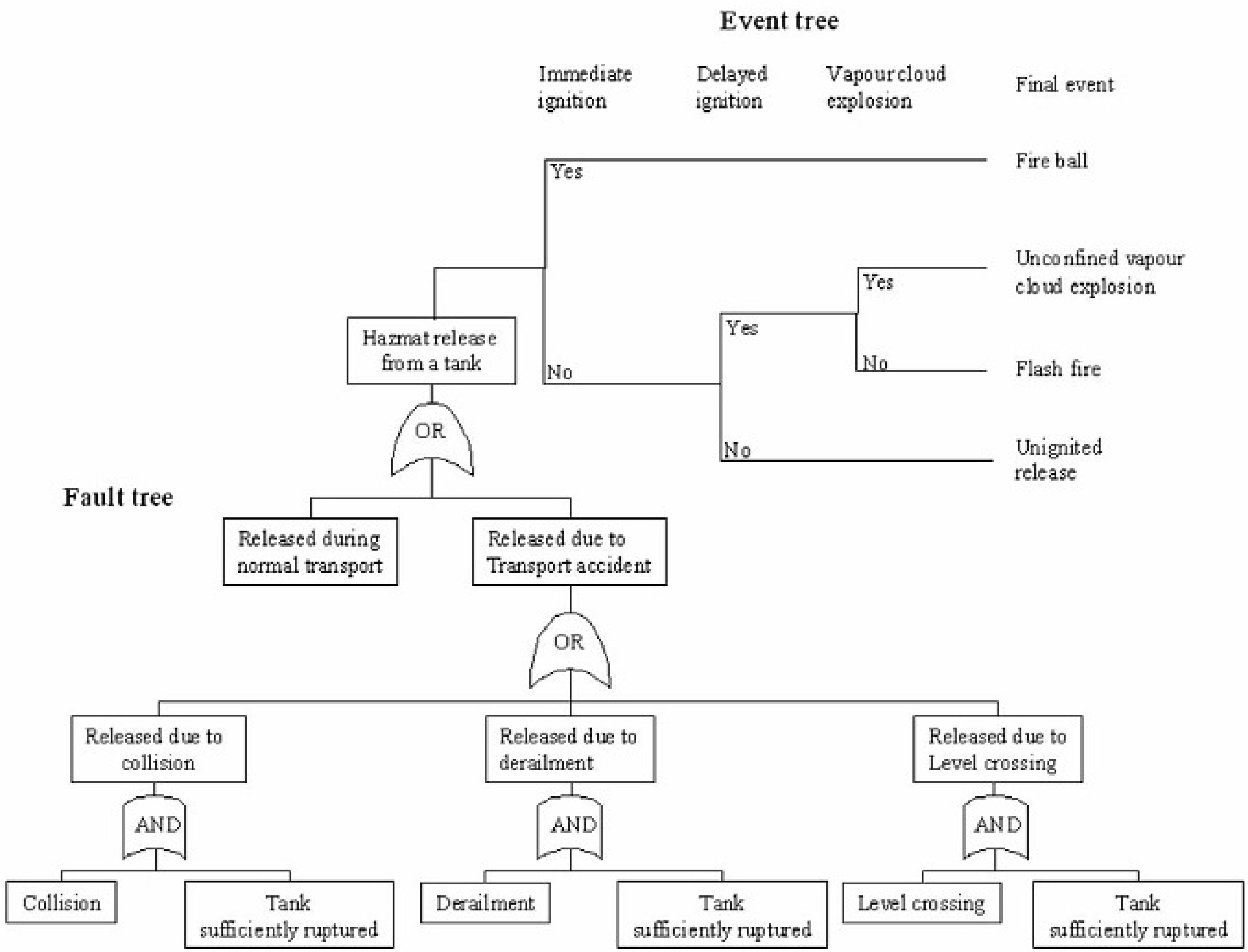

Fig. 5. A fault tree in conjunction with an event tree for hazmat release (adapted from Alp, 1995).

CONSEQUENCE MODELING AND RISK CALCULATION
Modeling the impact area

- There are many undesirable consequences of a hazmat transportation accident, such as *economic losses, injuries, environmental pollution, damage to wildlife, and fatalities*. These consequences are a function of the impact area (or exposure zone) and population, property, and environmental assets within the impact area.
- The shape and size of an impact area depends not only on the substance being transported but also on other factors, such as topology, weather, and wind speed and direction. Estimating, a priori, the impact area of a potential accident is difficult.
- Perhaps the **most common approximation of the impact zone is the danger circle**. By moving the danger circle along a route segment between two nodes (see Kara et al., 2003), we get the fixed-bandwidth approximation and by cutting off the circular segments at the two ends we get the rectangle approximation.
- The bandwidth or radius is substance-dependent but it is assumed to be constant for a given shipment, which means that this approximation does not consider effect of the distance on the level of impact. One can determine the radius by considering the evacuation distance (i.e., the initial isolation zone) when a hazmat incident occurs, for example, 0.8 km for flammable hazmats and 1.6 km for flammable and explosive hazmats (CANUTEC, 2004).

- *The central assumption in these models is that each individual within the danger zone will be impacted equally and no one outside of this area will be impacted*.
- The *modeling of an impact area can also be considered from the point of view of the affected population center*. *For example, a population center is commonly modeled as a point on the plane, where all inhabitants of the population center are considered to experience the same impact from a hazmat incident on a road segment nearby*. The impact on this aggregation point depends on the distance between the point and the incident location. For example, the impact can be inversely proportional to the square of the Euclidean distance between the two points.
- *However, a GIS enables researchers to represent the spatial distribution of population density more accurately rather than using aggregation points*.

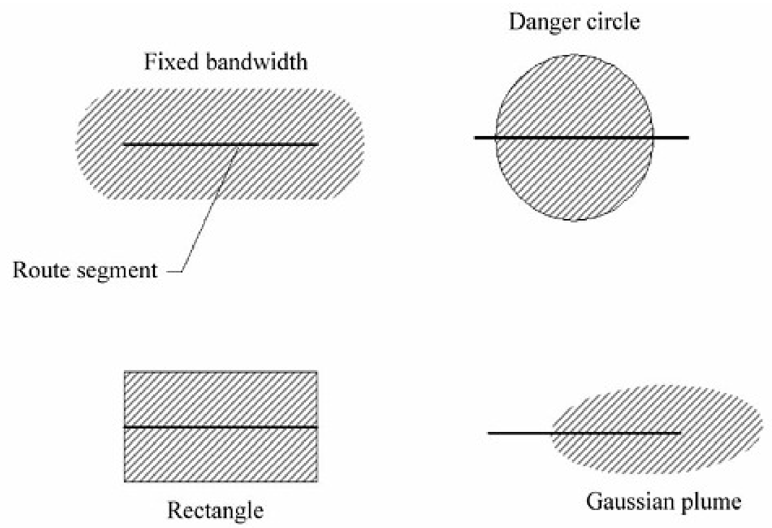

Fig. 6. Possible shapes of impact area around the route segment.

Gaussian plume model

- The Gaussian plume model is based on several limiting assumptions:

  (1) the gas does not change its chemical properties during dispersion;
  (2) the terrain is unobstructed and flat;
  (3) the ground surface does not absorb the gas;
  (4) the wind speed and direction is stable during the dispersion period; and
  (5) the emission rate is constant.

- These assumptions certainly limit the application of GPM, for example, assumption (1) restricts the applicability of the GPM to stable chemicals and to accidents which do not result in an explosion (Zhang et al., 2000). The GPMis formulated as

$$C(x, y, z, h_e) = \frac{Q}{2\pi \mu \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right) \times \left[\exp\left(-\frac{1}{2}\left(\frac{z-h_e}{\sigma_z}\right)^2\right) + \exp\left(-\frac{1}{2}\left(\frac{z+h_e}{\sigma_z}\right)^2\right)\right],$$

where $\boldsymbol{C}$ is the concentration level (mass per unit volume – μg/m^3 or parts per million – ppm), $\boldsymbol{x}$ is the distance downwind from the source (m), $\boldsymbol{y}$ is the distance crosswind (perpendicular) from the source (m), $\boldsymbol{z}$ is the elevation of the destination point (m), $\boldsymbol{h_e}$ is the elevation of the source (m), $\boldsymbol{Q}$ is the release rate of pollutant (mass emission rate – g/s or volumetric volume rate – m^3/s), μ is the average wind speed (m/s), $\boldsymbol{\sigma_y}$ and $\boldsymbol{\sigma_z}$ are the dispersion parameters in the $\boldsymbol{y}$ and $\boldsymbol{z}$ directions (m).

- In hazmat dispersion from traffic accidents, it is usually assumed that the source is on the ground (i.e., $h_e = 0$) and we are interested in the ground concentration level (i.e., $z = 0$). Therefore, we obtain

$$C(x, y, z, h_e) = C(x, y) = \frac{Q}{\pi \mu \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right).$$

- The release rate, ***Q***, depends on container volume, hazmat type, and rupture diameter. To calculate ***Q***, one can use ***ALOHA***. ALOHA can also be used for estimating the concentration level, $C(x,y)$, but its results are only reliable within one hour of the release event, and 10 kilometers from the release source. The dispersion parameters, σ_y and σ_z, can be determined as a function of downwind distance x (Pasquill and Smith, 1983; Arya, 1999).
- The individual risk, that is the probability that an individual at location j with coordinate (j_x, j_y) will experience an undesirable consequence (such as evacuation, or injury, or death) as a result of a release at i, p_{ij} ,can be represented as a function of the concentration of airborne contaminant at j,$C_{ij} := C(|j_x - i_x|, |j_y - i_y|)$.The American Institute of Chemical Engineers (2000) suggests a probit function to model $p_{ij} (C_{ij})$. Consequently, the social risk can be obtained by multiplying $p_{ij} (C_{ij})$ with the population size at location j.

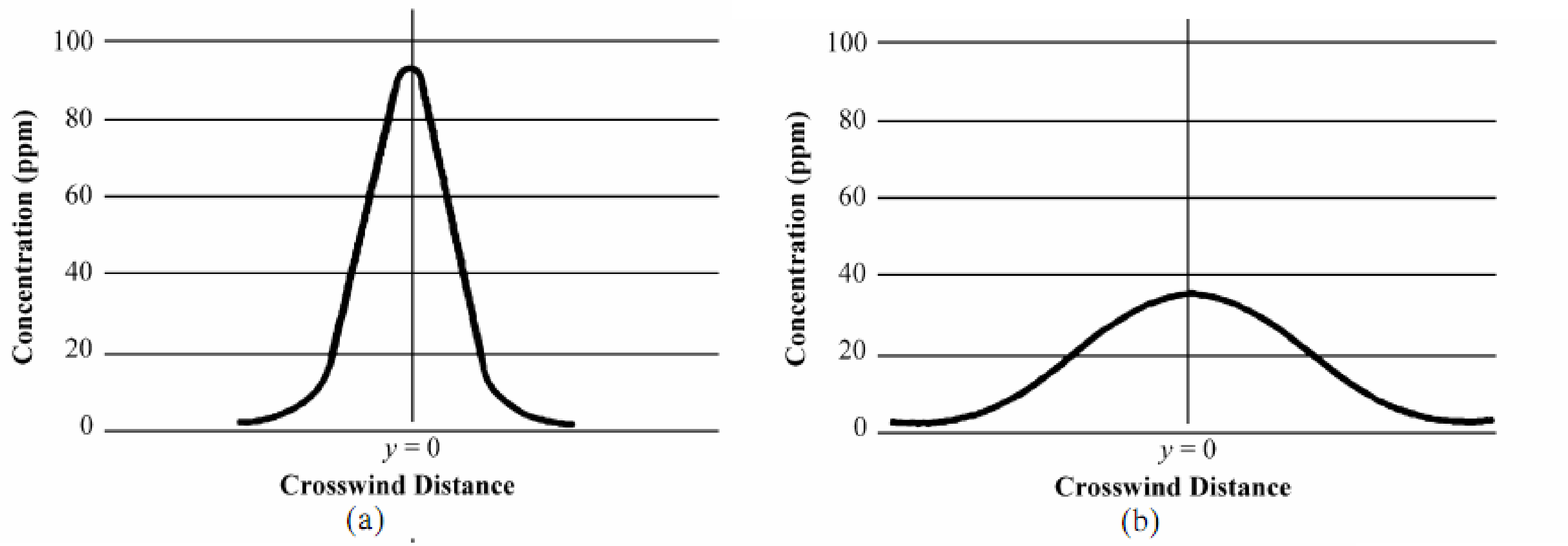

Fig. 7. The bell-shape of concentration level $C(x, y)$: (a) Gaussian distribution at $x = 0$ and (b) Gaussian distribution at $x \gg 0$ (Chakraborty and Armstrong, 1995).

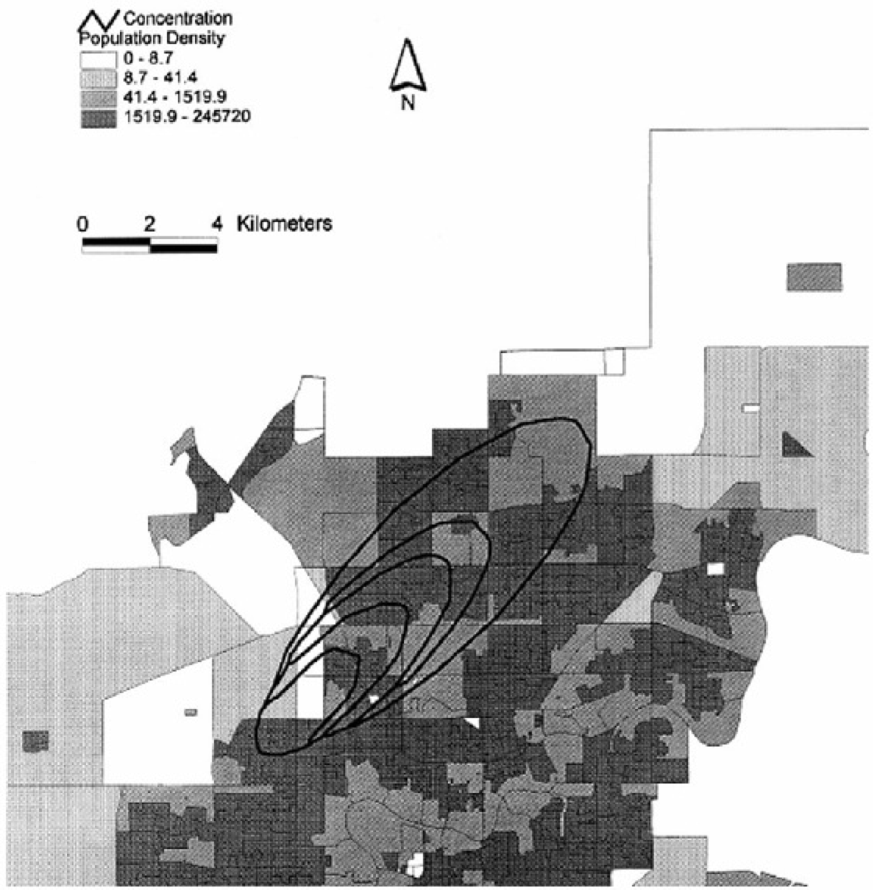

Fig. 8. Population densities within different concentration levels (Zhang et al., 2000).

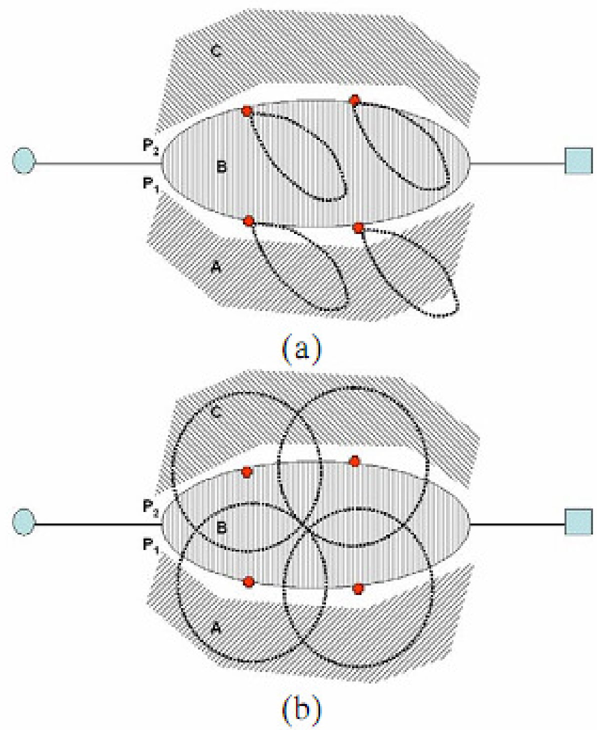

Fig. 9. (a) Gaussian plume model vs. (b) danger circle.

Risk cost

- To estimate the cost of a hazmat release incident, various consequences must be considered. The consequences can be categorized into (Abkowitz et al., 2001; FMCSA, 2001):
  - injuries and fatalities (or often referred to as population exposure),
  - cleanup costs,
  - property damage,
  - evacuation,
  - product loss,
  - traffic incident delay, and
  - environmental damage.
- ***All impacts must be converted to the same unit (for example dollars)*** to permit comparison and complication of the total impact cost. The discussion of risk costs presented here deals primarily with hazmat incidents on highways.

Injuries and fatalities

- Finding a dollar value of human life and safety is perhaps the most difficult and controversial issue. Some find it offensive; others argue that any dollar value assigned to human life would be too low. Yet it is possible to estimate the value indirectly.

- Insurance payments offer a simple estimate. Perhaps more relevant is the figure used by government agencies to In addition to the economic cost components discussed above, The National Safety Council (NSC) also includes the value of a person's natural desire to live longer or to protect the quality of one's life (NSC, 2003). This value indicates what people are willing to pay to reduce their safety and health risks.
- Finally, US DOT values injuries and deaths at the amount they would spend to avoid an injury or fatality (FMCSA, 2001). This averages out to be $400,000 to avoid an injury requiring hospitalization and $2,800,000 to avoid a fatality.

Cleanup costs

- Cleanup costs are assumed to encompass the costs of both stopping the spread of a spill and removing spilled materials (Abkowitz et al., 2001; FMCSA, 2001). Such costs vary widely depending on the size, type of materials, and location of the spill.
- For the period 1990–1999, cleanup costs averaged about $24,000 per en-route accident, $1300 per cleanup for an en-route incident spill, and $260 for an unloading/loading accident and incident spill cleanup (HMIS database).

Property damage

- Property damage encompasses damage to other vehicles, which may have been involved in the incident, as well as damage to both public and private property (e.g., private buildings, public utilities, public roadways).

- For example, from HMIS database of the period 1990–1999, the average property damage for flammable and combustible liquids en-route accidents was $16,041, while the average property damage for en-route incident spills was $274. Average property damage for leaks occurring during loading and unloading incidents and accidents was $68.
- Average property damage for flammable gases en-route accidents, en-route spills, and loading/unloading incidents were $3147, $173, and $2315, respectively. For corrosive materials, the average values for en-route accidents, en-route spill incidents, and loading/unloading incidents were $3104, $67, and $17, respectively (FMCSA, 2001).

Evacuation

- There are numerous variables which complicate the estimation of the cost of evacuation. These include the expense for temporary lodging and food, losses due to lost wages and business disruptions, inconvenience to the public, and the cost of agencies assisting in evacuation. A reasonable estimate would be $1000 per person evacuated (TRB, 1993).

Product loss

- Product loss refers to the quantity and value of the hazmats lost during a spill. For example, from the HMIS database for period 1990–1999, the average cost of product lost of flammable and combustible liquids en-route accident related spills was $3208 per spill. Similarly, for flammable gases accidents, the average cost of product lost per en-route accident related spill was $1140 per spill. Corrosive material spill accidents averaged $4910 per spill in product loss.

Traffic incident delay

- Hazmat spills typically require an emergency response that causes a significant traffic delay. This type of traffic delay is called incident delay. If traffic volume and incident situation (e.g., the traffic arrival rate, road capacity reduction, and incident duration) is known, a deterministic model can be used to estimate the incident delay.
- Earlier studies (Grenzeback et al., 1990) assumed the hourly cost of incident delay to be about $20 for trucks and $10 for other vehicles, which accounts for the value of a driver's time and fuel consumption costs. The total cost traffic incident delay is then obtained by multiplying this dollar value of incident delay with the total number of person hours of delay given by the model discussed above.

Environmental damage

- Environmental damage consists of damage to the environment that remains after the cleanup. This damage can be calculated in terms of loss of economic productivity, such as agricultural production lost and/or in loss of habitat or ecosystem deterioration (FMCSA, 2001). The loss of agricultural productivity can be estimated, for example, using the quantity of crops that are not grown during a 20-year period due to contamination. Using wheat as an example, a contaminated field that can produce 35 bushels per acre/year would result in an (undiscounted) gross income loss of $3500/acre over a 20-year period assuming a fixed value of $5/bushel. To calculate the natural resource environmental damage from a hazmat incident is more complicated. We need to know how much material was spilled, where the spill occurred, and what sort of surface it covered.