Risk-Based Decision Support Model for Planning Emergency Response for Hazardous Materials Road Accidents

by

Ghada Mahmoud Hamouda

A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Doctor of Philosophy

in

Civil Engineering

Waterloo, Ontario, Canada, 2004

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

ABSTRACT

Hazardous Materials (HazMat) are transported throughout Canada in a great number of road shipments. The transportation of HazMat poses special risks for neighboring population and environment. While HazMat accidents are rare events, they could be catastrophic in nature and could result in substantial damage to nearby communities. Effective emergency response plays an important role in the safe transportation of HazMat.

Transportation of HazMat involves different parties, including shippers, regulators, and surrounding communities. While the shipping party is responsible for safe delivery of HazMat shipments, it is the responsibility of local emergency service agencies to respond to accidents occurring within their jurisdictions. In this research, the emergency response to HazMat transport accidents is assumed to be delegated exclusively to specially trained and equipped HazMat teams.

This research proposes a new comprehensive systematic approach to determine the best location of HazMat teams on regional bases utilizing HazMat transport risk as a location criterion. The proposed model is the first to consider emergency response roles in HazMat transport risk analysis, and was intended as an optimization tool to be used by practitioners for HazMat emergency response planning.

Additionally, the proposed model can be used to assess risk implications in regards to current locations of HazMat teams in a region, and to develop effective strategies for locating HazMat teams, such as closing and/or relocating teams in the region. The model investigates how HazMat team locations can be tailored to recognize the risk of transporting HazMat and would provide a more objective set of input

alternatives into the multi-criteria decision making process of regionally locating HazMat teams.

The proposed model was applied to the region of southwestern Ontario in effort to illustrate its features and capabilities in the HazMat emergency response planning and decision making process. Accordingly, the model provided very useful insights while reviewing several HazMat team location strategies for the southwestern Ontario region and investigating tradeoff among different factors. This research contributes to a better understanding of emergency response roles by reducing HazMat transport risks, and will greatly benefit both researchers and practitioners in the field of HazMat transport and emergency response.

In the Name of God, the Compassionate, the Merciful

All praise to God Almighty

“Behold! in the creation of the heavens and the earth; in the alternation of the night and the day; in the sailing of the ships through the ocean for the profit of mankind; in the rain which Allah Sends down from the skies, and the life which He gives therewith to an earth that is dead; in the beasts of all kinds that He scatters through the earth; in the change of the winds, and the clouds which they Trail like their slaves between the sky and the earth;- (Here) indeed are Signs for a people that are wise.”

The Quran, English interpretation

Chapter 2, Verse 164

"Seeking knowledge is compulsory upon every male and female Muslim"

Prophet Mohamed (PBUH)

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my supervisors, Professor Frank Saccomanno and Professor Lee Fu for their encouragement and, advice during the course of this research.

I would like also to thank Mr. Barry Kendall from Fire Science Library, The Ontario association of fire chiefs, Mississauga, Hamilton, and Cambridge fire departments for the valuable information they provided on fire departments and HazMat emergency response in Ontario.

I acknowledge with gratitude the funding that I received in support of my research from:

- The Ontario Graduate Scholarship Program (OGS).
- The Natural Sciences and Engineering Research Council (NSERC) of Canada, through a Postgraduate Scholarship.
- The University of Waterloo, through the Provost/faculty of engineering Women's Incentive Fund Scholarship, and the Faculty of Engineering Graduate Scholarship.

I also would like to thank Mr. Robert Muhlbock for proofreading the final document.

And last but not least, I thank my family and friends who helped and supported me throughout the course of my academic endeavors especially my brother Khaled, and my dear friend Barbra Duran. I am truly grateful to Abeir and Emad Elbeltagy, I will never forget their favors.

I dedicate this work to my parents, Mahmoud and Faridah,

and my kids Radwa and Omar

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

AADT	Average Annual daily Traffic
ADS	Accident Data system
ALOHA	Areal Locations of Hazardous Atmospheres
ARCHIE	Automated Resource for Chemical Hazard Evaluation
BLEVE	Boiling Liquid Expanding Vapor Explosion
CANUTEC	the Canadian Transport Emergency Centre of the Department of Transport
CFR	Code of Federal Regulations (USA)
CHEMTREC	Chemical Transportation Emergency Center (USA)
DG	Dangerous goods (hazardous materials)
DGAIS	Dangerous Goods Accident Information System
GIS	Geographical Information System
HazMat	Hazardous Material (also known as Dangerous Good)
HSE	Health and Safety Executive (UK)
IDLH	Immediately Dangerous to Life and Health
INERIS	Institut National de l'Environnement et des Risques (France)
LFL	Lower Flammability Level
LPG	Liquefied Petroleum Gas
MVKm	Million Vehicle Kilometer
NFPA	National Fire Protection Association (USA)
ppm	parts per million

QRA	Quantitative Risk Assessment
TDGR	Transportation of Dangerous Goods Regulations, Canada
TDQRA	Time Dependant Quantitative Risk Assessment
UFL	Upper Flammability Level

GLOSSARY

- **BLEVE** — Boiling Liquid Expanding Vapor Explosion. A container failure with a release of energy, often rapidly and violently, accompanied by a release of gas to the atmosphere, followed by ignition (fireball) and propulsion of the container or container pieces.

- **Consequence** — the direct effect of an event. It is expressed as a health effect (e.g., death, injury, exposure), property loss, environmental effect, evacuation, or quantity spilled.

- **Containment** — Those procedures taken to keep a material in a specified area such as a dyke surrounding a tank or a temporary boom surrounding a spill etc.

- **Contamination** — The process of transferring a hazardous material from its source to people, animals, the environment or equipment which may act as a carrier.

- **Dangerous Goods (Hazardous**
  - *Office of Fire Marshal:* Hazardous material is any substance or form that may pose an unreasonable risk to health, safety or property. In Canada, the term "dangerous

Materials, HazMat) goods" is used to describe hazardous materials in transport and/or storage.

- *Transportation of Dangerous Goods Act:* dangerous goods/hazardous materials are any substances that pose an unreasonable risk to life, the environment or property when not properly contained.
- *Transportation of Dangerous Goods Regulations:* Dangerous Goods: means a product, substance or organism included by its nature or by the regulations in any of the classes listed in the schedule to the Act (see Schedule to the Act).
- *NFPA:* Hazardous Material A substance (solid, liquid, or gas) that when released is capable of creating harm to people, the environment, and property.

Schedule to the Act, Transportation of Dangerous Goods Regulations.

Class 1
Explosives, including explosives within the meaning of the "Explosives Act"

Class 2

Gases: compressed, deeply refrigerated, liquefied or dissolved under pressure

Class 3

Flammable and combustible liquids

Class 4

Flammable solids; substances liable to spontaneous combustion; substances that on contact with water emit flammable gases

Class 5

Oxidizing substances; organic peroxides

Class 6

Poisonous (toxic) and infectious substances

Class 7

Nuclear substances, within the meaning of the "Nuclear Safety and Control Act", that are radioactive

Class 8

Corrosives

	Class 9 *Miscellaneous products, substances or organisms considered by the Governor in Council to be dangerous to life, health, property or the environment when handled, offered for transport or transported and prescribed to be included in this class*

- **Distance to the endpoint** The distance a toxic vapor cloud, heat from a fire, or blast waves from an explosion will travel before dissipating to the point that serious injuries from short-term exposures will no longer occur.

- **Dose** The concentration of pollutant to which people are exposed, taken to a power, multiplied by the period of time that it is present. Some researchers refer to this quantity as "toxic load."

- **Emergency Response Facility** A structure or a portion of a structure that houses emergency response agency equipment or personnel for response to alarms.

- **Fireball** The burning of a flammable vapor cloud which is mostly above UFL. The whole cloud appears to be burning forming a mushroom shaped fire. The hazard is manly thermal.

- **Flash fire** The burning of a flammable vapor cloud at a very low flam propagation speed. The fire expands easily without significant overpressure. The hazard is only due to thermal effect.

- **Frequency** The rate at which events occur. It may be expressed as event/year, accidents/km, and so on.

- **Hazard** A chemical or physical condition that has the potential for causing damage to people, property, or environment.

- **Hazardous Materials** See "Dangerous Goods"

- **Hazardous Materials Response Team (HazMat team)** A group of trained response personnel operating under an emergency response plan and appropriate standard operating procedures to control or otherwise minimize or eliminate the hazards to people, property, or the environment from a released hazardous material.

- **IDLH** Immediately Dangerous to Life and Health. The maximum level of concentration from which one could escape within thirty minutes without any escape impairing symptoms or health effects.

- **Incident** An occurrence or event that requires action by emergency service personnel to prevent or minimize loss of life or damage to property and/or natural resources.

- **Individual risk** The relationship between a given level of harm from the realization of a specific hazard and the frequency at which an individual may be expected to sustain that level of harm.

- **Leak** A small, sporadic discharge, emission or escape of product from means of containment. The release of product usually is of a long duration.

- **Likelihood** A measure of the expected probability or frequency of occurrence of an event. This may be expressed as frequency (e.g. events/year), a probability of occurrence during some time interval, or a condition probability.

- **Liquefied Petroleum Gas** Petroleum gases which can be liquefied under moderate pressures. Common LPGs are butane and Propane.

- **Lower Flammable Limit (LFL)** The lowest concentration (lowest percentage of the substance in air) that will produce a flash of fire when an ignition source (heat or flame) is present. At concentrations lower than the LEL, the mixture is too "lean" to burn.

- **Mitigation time** Time to apply mitigation measures at the site, mainly containment and evacuation.

- **Quantitative Risk Assessment** Incorporates numerical estimates of frequency and the consequence in a sophisticated but approximate manner to estimate quantitative measure of risks.

- **Release** A release of HazMat load excluding any spill or leak from the vehicle fuel tank.

- **Response time** Consists of three components; dispatch time at the emergency response facility, travel time from the emergency response facility to the release site, and time to start mitigation at the site (mainly containment and evacuation).

- **Risk** A measure of potential economic loss, human injury, or environmental damage in terms of both the incident likelihood and magnitude of the loss, injury, or damage.

- **Risk (transport risk)** The expectation of fatalities that results from the transport of a certain volume of different types of HazMat on different links of the road network. This risk consists of two fundamental components: the frequency of HazMat accident induced releases and their consequent damages during transport

- **Risk Assessment** An assessment of the likelihood, vulnerability, and magnitude of incidents that could result from exposure to hazards.

- **Societal risk** the relation between frequency and the number of people affected by a specified level of harm in a given population from the realization of specified hazards

- **Spill** A spill is defined as an immediate or continuous discharge, emission or escape of product from means of containment. Typically the release of product is of a short duration.

- **Upper Flammable Limit (UFL)** The highest concentration of a vapor or gas that will produce a flash of fire when an ignition source (heat or flame) is present.

CHAPTER 1: INTRODUCTION

In recent years, the industrial part of our society has experienced rapid growth. However, while industries such as chemical, nuclear, electrical and petroleum, benefit the world, they also come with complications. Industries consume hazardous materials in their production and generate hazardous substances as byproducts or waste. As a result, great amounts of hazardous materials are transported over highways and mass-transit networks in order to be disposed of in proper facilities.

Office of the Fire Marshal (2003) defines Hazardous Material as “a substance that poses a risk to life, the environment, or property, when released from its container.” The terms “Dangerous Goods,” “Hazardous Materials” and “HazMat,” essentially, refer to this same category of substances. In Canada and Europe, the term “Dangerous Goods” is used in transport-related situations, while the words “Hazardous Material” or “HazMat” are used in activities related to emergency response. In the USA, the term “Hazardous Materials” or “HazMat” is widely used for both transport and emergency response activities. Accordingly, this thesis will henceforth use the terms “HazMat” to refer to “Dangerous Goods” and “Hazardous Materials” (see Glossary for additional definitions of these terms).

1.1 Background

There are approximately 500,000 hazardous commercial products transported in Canada (U.S. Department of Transportation et al. 2000), about 3,000 of which are regulated under the Transportation of Dangerous Goods Regulations (TDGR), including flammable, corrosive, radioactive, toxic and poisonous substances (Transport Canada 1992).

HazMat are transported throughout Canada in a large number of road shipments and amount of tonnage. According to Transport Canada (2003), there are approximately 30 million shipments of HazMat every year that are subject to the TDGR. Moreover, about 93% (25 million) of all HazMat shipments are made by road—a tonnage totaling over 128 million—with the province of Ontario coming second only after Alberta in HazMat road tonnage transported. Among the four modes of transport (road, rail, marine, and air), 90% of reportable accidents occur on road, an average of 156 HazMat road accidents per year while in transit. Appendix A gives an overview of HazMat movements and accidents in Canada.

1.1.1 HazMat Transportation Risk

Transportation of HazMat poses special risks for the neighboring population and environment. While HazMat accidents are rare events, they can lead to catastrophic consequences. For instance, on July 11, 1978, a Propane cargo tank passing near a campground in Spain exploded killing an estimated 200 people and badly burning another 120 (US Department of Transportation, Research and Special Programs Administration 1997). The following are two examples of HazMat road accidents:

- US Department of Transportation, Research and Special Programs Administration (1997): On July 27, 1994, in White Plains, New York, tractor cargo-tank semitrailer struck a column of an overpass and ruptured, releasing 9,200 gallons of Propane (a liquefied petroleum gas) which was later ignited. The driver was killed, 23 persons were injured and an area within a radius of 400 feet was engulfed in fire.
- National Transportation Safety Board, US (1991): In 1991, a tractor-semitrailer carrying 8,800 gallons of Gasoline overturned on a main urban roadway in Carmichael, California. Gasoline from the cargo tank spilled into the drainage ditch which extended under the roadway and behind private residences nearby. About 15 minutes after the overturn, the Gasoline ignited and the subsequent fire engulfed the overturned cargo tank. Four homes were heavily damaged by the fire, and the residents from a 2-mile-square area were evacuated. The total property damage and cleanup costs were estimated at nearly $1 million and three minor injuries were reported.

Ironically, certain HazMat are transported on the road network in quantities that would exceed the threshold for safety if stored in a fixed facility. Moreover, recent analyses as well as historical events have shown that risks arising from the transportation of HazMat are often of the same magnitude as those resulting from fixed facilities (Fabiano et al. 2002). A search of the literature covering the time span 1926 through 1997 revealed reports of 3,222 accidents related to the handling, transportation, processing, storage of chemicals involving different types of HazMat, of which 54% were related to fixed facilities, 41% were transportation accidents and 5% miscellaneous accidents (Khan & Abbasi 1999). In a study based on the 1983 Commercial Vehicle Survey, Gorys (1987) found that about one third of all HazMat releases in Ontario resulted from transportation-related incidents. As a result, given that transportation activities take place beyond the control of fixed facilities, there is a justifiable concern that HazMat be transported in the safest possible manner.

1.1.2 Definition of HazMat Risk

The National Fire Protection Agency (2004) defines "risk" as the measure of probability and severity of adverse effects that result from exposure to a hazard. As a result, HazMat risk is commonly defined as a function of HazMat release frequencies and the subsequent damages resulting from such releases (Rhyne 1994, Center for Chemical Process Safety 1995). Frequencies of HazMat releases depend on many factors including the probability of an accident, the conditional probability of release given an accident, the probability of a certain release size taking place, and the volume of HazMat movements (Rhyne 1994).

Consequences of a HazMat release depend on the type of transported HazMat, the amount released, meteorological conditions, ignition probabilities, potentially exposed population, and the time interval between the initial release and the initiation of mitigation procedures. At the road network level, HazMat transport risk is commonly expressed as the summation of risk over all likely accidents and possible damages for different HazMat types, transportation/accident scenarios, and release locations.

HazMat accidents near highly populated areas pose the largest risks due to the considerable number of potentially affected people. Also, areas prone to high frequencies of HazMat releases have greater risk levels. Delays in response to HazMat incidents can result in appreciable consequent damages to people and property. For example, the release of toxic chlorine from a bulk tanker can continue for up to 24 hours and may result in a higher threat if left unattended. The response time factor is especially significant for the transport of HazMat, which includes a strong possibility that releases may occur at considerable distances from the nearest emergency response unit. Releases that take place in remote areas can cause higher damages, since emergency response to such areas depends on facilities located at some distance in larger municipalities.

1.1.3 HazMat Emergency Response

The transportation of HazMat involves many different parties, including the shippers, the regulators, and the communities the materials must pass through. While the shipping party is responsible for the safe delivery of HazMat shipments, HazMat accident response emergency response is the responsibility of local emergency services based on their respective jurisdictions. In this research, the response to accidents involving HazMat is assumed to be delegated exclusively to specially trained and equipped HazMat teams performing the needed duties. The National Fire Protection Agency (2004) defines the HazMat team as an organized group of trained response personnel, operating under an emergency response plan and appropriate standard operating procedures, who handle and control actual or potential leaks or spills of hazardous materials requiring possible approach to the material.

Providing efficient emergency response measures throughout the road network can substantially reduce HazMat transport risks. As recommended by the US Federal Emergency Management Administration, US et al. (1989), emergency response to minimize the consequence of HazMat releases generally involves the following procedures[1]:

1) Plugging/stopping of leaks

Completely or partially plugging a leak source is often the first step to effective control of HazMat release. The most widely available means of plugging holes or leaks involves the use of conical, cylindrical, square or wedge shaped pieces of wood rubber or metal sheets, and clamps of various types. Many incidents are brought to a rapid end simply by having the proper tools to close a valve or tighten some bolts. However, in the absence of these tools, other means of reducing the spillage of HazMat can sometimes be employed. For example, if feasible, the outflow of HazMat may also be reduced by turning the body of the vehicle over such that the point of leakage rises.

[1] See also United States Fire Administration *Hazardous Materials Response Technology Assessment*, undated manual.

2) Containment of spilled liquids or solids on land

Specialized equipment has been developed to construct dikes of foamed concrete or plastic materials in the event of a land spill. However, earth, sand, clay and plastic or rubber sheeting are widely available and generally adequate to use.

3) Removal of spilled liquids or solids on land

Once the spilled substance has been contained, removing it from the environment is the next task. Pumps, hoses, and tanks, drums, or vacuum trucks might be used to collect pools of accumulated liquids, while shovels, loaders and other earth moving equipments may be used to remove contaminated soil.

4) Suppression of hazardous gas or vapor releases

The following list represents several response measures that may be used to reduce the rate or mount of airborne contamination, either direct or via evaporation from pool:

- **Physical restriction of liquid pool surface areas**: Evaporation rate from pool is directly related to pool surface area. Thus, reducing pool surface area by means of building dikes or digging trenches reduces the evaporation rate.
- **Use of specialized foams on liquid pools**: Once the pool area has been confined, a thick foam blanket may further reduce evaporation even from pools of liquefied gases.

- **Dilution or coverage of liquid pools with water or other compatible and safe liquids**: If feasible, diluting liquid pools with water or other safe liquids helps reduce evaporation.
- Use of water sprays or fogs: Water sprays or fogs from fire hoses and nozzles could be used to knockdown, absorb, or disperse hazardous vapors in the air.
- Neutralization of spilled liquids: Several HazMat can be neutralized via a chemical reaction to other substances that pose lesser threats to public health or the environment.
- **Cooling of spilled liquids or leaking containers:** Using ice, dry ice, or, if possible, liquid nitrogen to cool down spilled liquids or leaking containers could reduce the evaporation rate.

Responding to accidents involving HazMat requires a high level of training and special equipment. The National Fire Protection Agency (NFPA) 472 Standard (1997) defines different levels of training and competencies for the HazMat team's personnel. A HazMat team typically consists of many specially trained firefighters equipped with body protection suits, containment, decontamination equipment, and expertly trained in the following duties: 1) analyzing a hazardous materials incident and collecting hazard and response information; 2) identifying the potential action options (defensive or offensive); planning and implementing response operations; and 3) evaluating the progress of the planned response.

Emergency response systems tend to be multi-purpose in nature. Thus, responding to HazMat releases represents only one of the many tasks involved in emergency response. The location of HazMat teams based solely on proximity to potential release sites is impractical since this distribution could result in high service and infrastructure costs. As a result, hosting HazMat teams within existing fire stations is a more common and cost effective practice. Such multitask teams can respond to HazMat accidents when needed, or otherwise carry out ordinary fire fighting responsibilities, keeping initial costs to practical limits. A description of typical HazMat team may be found in Appendix B.

HazMat emergency response planning has traditionally been the responsibility of local authorities. In Canada, it is the municipalities' responsibility to assess the need for, as well as provide, different levels of HazMat emergency response capabilities (Office of the Fire Marshal 1998). In its 1998 Public Safety Guidelines, Office of the Fire Marshal provides the following guidelines for HazMat emergency response planning:

1. Identify the nature and extent of HazMat risks.
2. Establish service levels needed.
3. Provide resources and identify the most effective use of them to obtain the desired service level.
4. Project HazMat locations and re-locations.
5. Determine staffing levels and assignments.
6. Implement a management evaluation system to review the effectiveness of the implemented plan.

The US Federal Emergency Management Agency (1998) and the US Environmental Protection Agency (1990) provide similar guidelines in the Unites States. Among the activities eligible for funding from the U.S. Department of Transportation, the USA Code of Federal Regulations 49 CFR part 110.40 includes, “the assessment of the need for regional hazardous materials emergency response teams” and “the assessment of local response capabilities” (US Code of Federal Regulations 2003). Establishing the number and location of HazMat teams is among one of the most important aspects of HazMat emergency response planning. Hence, effectively locating HazMat teams on the transportation network can reduce consequent damages from HazMat releases by reducing the time of damage propagation.

1.2 The Problem

HazMat accidents can result in substantial damage to nearby communities if they occur in areas lacking emergency response capabilities (Rowe 1983). Thus, effective emergency response plays an important role in the safe transportation of HazMat. Facilities that produce and use HazMat are often well equipped with appropriate emergency response capabilities. However, communities might have large amounts of HazMat transported over their road networks, despite their lack of industries that use or produce HazMat. Accordingly, HazMat transport-related accidents can occur away from established facilities and, as a result of their remoteness, insufficient response time to such incidents is usually the outcome.

Chapter 1

Currently, planning HazMat emergency response is carried out at the local level with no standardized systematic method for the planning process. Moreover, many smaller municipalities find establishing their own comprehensive HazMat teams to be financially challenging. The high cost of establishing a well-equipped and trained HazMat team necessitates careful planning; however, little coordination among different municipalities exists when planning HazMat emergency response. The following points elaborate on different aspects of this problem:

1. There is a lack of systematic integrated method for locating HazMat teams on a regional bases. Existing guidelines for HazMat emergency response planning have recognized the importance of effective HazMat team locations. However, no specific regulations or recommendations that govern the location of HazMat teams are present, nor is there a systematic procedure for locating them. Moreover, a maximum acceptable response time role for responding to HazMat accidents has never been decided upon. Thus, as Champlain (1999) affirms in his research, technical advisors and industry response teams have been given no standards, regulations, or guidelines in relation to the minimum acceptable response time in case of HazMat emergencies. Currently, HazMat team location decisions are carried out through intuition and educated guesses that depend mainly on the availability of funds, the potential population exposure, and the history of HazMat accidents in the area—a practice that usually favors highly populated areas. However, while many communities have neither the population nor industrial activities needed to justify the placement of

HazMat teams, they might be situated in proximity to routes where large amounts of HazMat are transported.

2. There is a lack of coordination among different municipalities in planning HazMat emergency response services. In many jurisdictions, decisions concerning the establishment and management of HazMat teams are undertaken at the local level (Office of the Fire Marshal 1998). However, local authorities usually work separately from each other with no or minimal co-operation on team location decisions.
   From large urban communities to rural townships, local municipalities may vary considerably. While large municipalities, with high population concentrations and well-established industrial facilities, can foresee and meet their HazMat emergency response needs, many smaller municipalities may not have such resources. Moreover, when one considers that HazMat teams are usually located at existing fire stations—a feature of large municipalities—the idea that smaller municipalities have insufficient coverage becomes even more apparent. More importantly, no guarantee exists that this approach will lead to an efficient allocation of resources in regards to minimizing the risks from HazMat transport or ensuring that all communities in the region are served to some minimum acceptable standard.

3. Lack of coordination in locating HazMat teams results in a miss-allocation of valuable resources and may lead to insufficient coverage and unacceptably long response times for the majority small municipalities (low populated, remote areas). Moreover, since much of the road network lies within these rural areas, the result is

poor service for much of the HazMat travel distance. Conversely, larger municipalities have the potential to over-compensate by stationing too many HazMat teams in close proximity. Smeby (1997) indicated that during since the 1980's there has been an explosion in the number of HazMat in some parts of the United States. Furthermore, since the formation of these teams, many have rarely been called to duty, with the average dispatch number being "once every year." Given this statistic, and also due to limited resources, many jurisdictions have begun to question the need for separate HazMat teams at specific locations and instead suggest a consolidation of teams in larger communities.

4. Given the high level of training and the special equipment needed for HazMat emergency response, the cost of providing HazMat teams is relatively high. According to the San Bernardino County Fire Department (2004), initial training for emergency responders can exceed 200 hours of instruction, with specially outfitted vehicles ranging in cost from $50,000 to $250,000 or more. The Vancouver fire department estimated that $326,400 worth of new specialized equipment is needed to improve its existing two HazMat teams (Howell 2004).
   Furthermore, resources to provide the HazMat emergency services are often limited. According to the Office of the Fire Marshal (1998), most fire protection agencies are currently experiencing escalating demands for emergency response, including HazMat accidents. Many departments are scrambling to meet increased training needs and to purchase equipment and supplies necessary for the safe handling of HazMat accidents.

Such high costs and limited resources necessitate careful planning when deciding how many HazMat teams should be provided, and where they should be stationed. A better utilization of available resources is needed so that regional bases can be assured efficient coverage; yet, this coverage is even more significant for the road network. Facilities that produce and/or use HazMat within communities are usually well equipped and ready to deal with events in case of an emergency. On the highways, however, response time to an incident may not be prompt enough or sufficient.

5. Enhanced HazMat team locations are of crucial importance for effective response to HazMat transport-related accidents. HazMat accidents while in transport may occur at considerable distances from the nearest emergency response unit. Thus, locating HazMat teams near major population concentrations, or locating teams close to sites with high potentials for transport-related HazMat accidents, is a dilemma that must be considered. Unfortunately, these objectives run counter-productive to each other in many cases. In Ontario, for example, much of the population is located in the southern part of the province near Toronto, whereas the bulk of the regional highway mileage is located in sparsely populated and remote northern areas.

   There are many important factors that should be considered when planning HazMat emergency response, including population at risk, accident and release frequencies, the type of HazMat, level of hazard associated with it, as well as the time needed for response. These factors are all associated with HazMat risk. However, while the US Federal Emergency Management Agency (1989) acknowledges the need for a comprehensive HazMat response plan to ensure that risk to the entire region (all communities) is taken into account in locating of HazMat teams, current practice in stationing HazMat teams considers only some of these factors. Thus, the need to utilize risk minimization on regional bases as a criterion for locating HazMat teams is necessary to provide a platform that accounts for all risk factors. HazMat emergency response coverage should also include a maximum acceptable response time and maximum acceptable level of risk on the entire network.

1.3 Research Objectives

HazMat emergency response planning is a multi-criteria decision making (MCDM) process. The decision of where to locate a HazMat team depends on the need for HazMat emergency response services as well as many other criteria including physical, legal, financial, managerial, and political considerations. In multi-criteria decision making processes, given a set of alternatives and a set of decision criteria, different alternatives are to be evaluated according to the different evaluation criteria (Triantaphyllou 2000). Each alternative has its own strengths and weaknesses and usually no one alternative outperforms the others in all areas. The proposed model will help to provide a more objective set of input alternatives into the multi-criteria decision making process of regionally locating HazMat teams.

This research aims to achieve the following objectives:

1. To develop a risk-based optimization location model that can be used as an effective procedure to determine the optimum number and location of HazMat teams on a regional road network. The proposed model adopts a risk-based optimization

technique with the objective of efficiently locating/relocating HazMat teams on a regional road network using HazMat risks as a location criterion.

The proposed model consists mainly of two components: a) a Time-Dependant Quantitative Risk Assessment (TDQRA) module that considers the temporal behavior of HazMat releases and accordingly estimates the risk for the entire road network and at its specific nodes; and b) a location optimization module for locating HazMat teams on the network based on the risk involved. The Time-Dependant Quantitative Risk Assessment (TDQRA) module can be used to assess HazMat transportation risks, to identify parameters that influence the level of risk, to develop new emergency response risk reduction strategies, and to evaluate new HazMat transportation policies. The location module would seek the most efficient locations of HazMat teams on the network such that network risk is minimized region wide, while ensuring that the response time at more remote locations does not exceed some preset thresholds.

The proposed model can be used to assess the risk implications of the current location of HazMat teams in a region, assess the sufficiency of the current teams, and identify areas lacking coverage on a regional basis. The model can be used to develop cost effective strategies for locating HazMat teams, including closure or relocating of some teams in the region. The model would help investigate how HazMat team locations can be tailored to recognize the risk of transporting HazMat and would help provide a more objective set of input alternatives into the multi-criteria decision making process of regionally locating HazMat teams.

2. To apply the proposed risk-based location optimization model to a case study (i.e. southwestern Ontario region) to illustrate its features and capabilities in the HazMat emergency response planning and the HazMat team location decision-making process. The HazMat team locations model would be used to review several HazMat team locations strategies and investigate tradeoff among different factors. The model would be applied to the investigation of the following issues: 1) The risk implications of the existing and the optimal location of the HazMat teams in the region, 2) The effectiveness of this system as compared to a system comprising of fewer HazMat teams, 3) The impact of the number of HazMat teams on the network-wide risk, 4) The difference in emergency response needs for different types of HazMat, 5) The effect of different HazMat routing strategies on planning HazMat emergency response, and 6) The environmental impact of HazMat releases and how different emergency response strategies affect the severity of such impacts.

3. To perform sensitivity analysis to test the robustness of the model to uncertainty and errors in input data and model parameters, such as HazMat traffic volumes, HazMat accident data, and travel time.

4. To implement the above model as user-friendly software tool that can be used by planners to meet their HazMat planning needs.

The system will help provide a set of best feasible HazMat team location solutions as a support in the multi-criteria decision making process of choosing HazMat team locations. The system will help answer such questions as: Are current HazMat teams sufficient to provide emergency response coverage? Will implementing certain recommendations, such as increasing or relocating certain teams, significantly reduce risks? Which design alternatives will minimize risks at acceptable costs? Moreover, the system will allow local and regional authorities to allocate resources in an effective way toward areas that pose the most significant risks as well as provide a better means to plan emergency response efforts.

1.4 Research Scope

The scope of this research is limited to the following five aspects:

1. **Road transportation:** This research is limited to road transportation of HazMat. Rail, marine, and air transportation of HazMat are not considered. The analysis focuses on HazMat accidents while in transport, excluding incidents while loading/unloading, at stop or in storage.

2. **Regional network:** Given the increasing need for HazMat emergency response services and the limited availability of resources, regionally optimized location of HazMat teams will ensure the efficient coverage of the whole region, and at the same time accounts for the economics of providing these services. Hence, this research focuses on the regional aspect of emergency response to HazMat accidents while in transit.

3. **Locating HazMat to basic units (existing fire stations):** HazMat teams are usually hosted within existing fire stations to keep initial and operational costs within practical limits. Establishing fire stations solely on the basis of response to HazMat accidents is impractical and costly since responding to HazMat incidents accounts for only a small part of the total emergency response service. The candidate locations for HazMat teams are therefore restricted to current fire stations. It should be noted that such restriction might result in insufficient coverage, especially for remote areas. Thus, additional analysis will be performed to examine this potential problem and how the relaxation of this location restriction might affect HazMat risks in the region.

4. **Limited HazMat types and release events:** The model to be developed aims at providing a means to study those risks associated with the road transportation of HazMat that have the potential to present major hazard accidents, such as fire and toxic releases within a certain region.

   There are more than 3000 regulated HazMat substances in Canada, most of them either toxic or flammable. Button (1999) stated that 65% of road kilometers by trucks carrying HazMat loads are flammable liquids, and 24% are toxic liquids while the remaining 11% accounts for all other types of HazMat. Although different types of HazMat have different risk attributes in terms of the danger level and propagation speed after release, a full consideration of all HazMat types is time consuming and impractical since each HazMat type requires a corresponding different risk model. As a result, this research will be limited to those HazMat types judged to result in significant hazard. The four selected HazMat classes are, toxic liquefied gas (represented by Ammonia), flammable liquefied gas (represented by Propane), flammable liquids (represented by Gasoline), and toxic liquids.

Ammonia and Propane are selected because they are considered to be potentially the most hazardous, as confirmed by historical analysis (Fewtrell, and Siddique 1998). Gasoline is selected on the basis that it is transported in significantly large quantities over the road network, and toxic liquids are considered for their potential high environmental hazard. These selected types of HazMat are intended to be representative of other similar hazardous materials.

5. **Discrete location problem:** The HazMat transport accidents and the demand for HazMat emergency response services can occur at any point on the road network. However, considering all possible accident locations is both time and resource consuming as well as practically unachievable. To simplify the formulation of the problem, the continuous demand on road segments is substituted with a discrete set of demand nodes. Accidents occurring on links are aggregated to the nearest nodes, and HazMat team locations are restricted to a pre-defined set of candidate nodes (existing fire stations).

6. **Deterministic modeling**: In developing the model, a large number of input parameters will be used. Many input parameters are stochastic in nature, assuming a range of values with some probability distribution. This stochastic nature of the

problem will not be addressed in this model and only point estimates will be used for different input parameters.

1.5 Thesis Organization

This thesis is organized into the following chapters. Background and related literature is discussed in Chapter 2. Chapter 3 introduces the proposed risk-based HazMat team location optimization model with its components, the TDQRA module and the location optimization module. The frequency and consequence analysis calculations are discussed in Chapters 4 and 5, respectively. A description of the southwestern Ontario case study is covered in Chapter 6 with a sensitivity analysis to determine its robustness to uncertainty in input parameters. Chapter 7 illustrates the model features and potential application through the investigation of several HazMat team location policies. Finally, conclusions, recommendations and future work are stated in Chapter 8.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

The problem of locating HazMat teams in a region involves many study areas including transportation of HazMat, quantitative risk assessment and location optimization techniques. This Chapter provides an overview of these related topics, with more detailed background provided in subsequent chapters.

2.1 Research Topics in HazMat Transport

Much of the academic research in the area of transportation of HazMat has focused on the problem of HazMat logistics and facility site location. Research topics in HazMat logistics include routing and scheduling of HazMat movements such that risk, exposed population, travel time, or accident frequency is minimized. In the facility siting problem, the best location for a new facility that produces, uses or stores HazMat is addressed. A review of various research topics associated with the transportation logistics of HazMat can be found in Erkut and Verter (1995) and List et al. (1991). Kara and Verter (2004), Zografos and Androutsopoulos (2004), Leonelli et al. (2000), Frank et al. (2000), Marianov and ReVelle (1998), and Sivakumar et al. (1995) illustrate some of the recent research carried out in these areas. Although much research has been devoted to transportation of HazMat, little has been done to incorporate emergency response into the risk assessment of HazMat accidents.

2.2 *Current Practice in Locating HazMat Teams*

HazMat emergency response planning has traditionally been the responsibility of local authorities. According to the Office of the Fire Marshal (1998), the responsibility to assess the need for HazMat emergency response services and accordingly provide different levels of response capabilities lies with respective municipalities. In 1998, the Office of the Fire Marshal published "Public Fire Safety Guidelines" to provide municipalities with guided options and assistance when determining the level of hazardous materials response capability provided to the public. The US Federal Emergency Management Agency (1998) and the US Environmental Protection Agency (1990) provide similar guidelines for HazMat emergency services in the United States.

Currently, the practice of locating HazMat teams is carried out through guidelines, intuition and educated guesses, and depends mainly on the availability of funds, potential population exposure, and the history of HazMat accidents in the area. There are no known Federal or Provincial regulations governing the number and/or location of HazMat emergency response teams. Moreover, there are no standards for the minimum acceptable response time that HazMat teams should follow. Champlain (1999) found that there were no standards, regulations, or guidelines dealing with the minimum response time acceptable in case of HazMat emergencies which technical advisors and industry response teams should abide by. However, he noted that "some" police departments, fire stations and ambulance services set their own standards separately. Frequently HazMat teams are located in areas of high population concentration (larger communities in the region), at the expense of under-serviced marginal locations that are also exposed to HazMat risks.

Both fire stations and HazMat teams are usually located through subjective studies with minimal or no co-operation among different communities. Given the subjective nature of the current practice in HazMat teams planning, the location in a given region can lead to a miss-allocation of resources and higher risks. An example of one such subjective study is the 2001 report conducted by TriData Corporation of Arlington, Virginia, US (2001). TriData performed an analysis of the consolidation options for the HazMat teams in the two cities of South Milwaukee and Cudahy, Wisconsin. The study was based on interviews, observations, and comparisons with other communities, and recommended full consolidation of the two fire departments, specifically identifying “Hazardous materials response” as one of the components recommended in the case of a partial consolidation.

Some attempts have been done to regionally assess HazMat emergency response teams. For example, the State of Wisconsin, Legislative Audit Bureau (2002) conducted a comprehensive state-wide study to evaluate the activities and expenditures of Wisconsin’s regional hazardous materials response teams. Most Wisconsin communities are served by volunteer or part-time fire departments that cannot afford to maintain specialized teams. Therefore, the Division of Emergency Management at the Department of Military Affairs contracted with ten municipal fire departments to provide regional coverage for incidents requiring the highest level of response. The study was subjective in nature, applying a survey methodology to assess the currently available HazMat emergency services.

2.3 Planning of HazMat Teams and Emergency Response

HazMat emergency planning is mainly carried out for post-accident management. In North America, governmental agencies provide handbooks, manuals, and telephone hotlines to help emergency response in post accident emergency response. Examples include the North America Emergency Response Guide Book (Transport Canada et al. 2000), the Canadian Transport Emergency Centre of the Department of Transport (CANUTEC) which provides emergency response information and assistance on a 24-hour basis for the responders to hazardous materials incidents, and the equivalent US Chemical Transportation Emergency Center (CHEMTREC).

Past research on HazMat team planning has mainly focused on several areas, including the development of decision support systems for hazardous materials emergency response operations (Zografos et al. 2000), the assessment of HazMat response preparedness (Aini et al 2001, Cannon et al. 1998, and Hancock et al. 1993), the evaluation of the efficiency of HazMat programs (US Department of Transportation 2000), HazMat emergency response training (Zeimet & Ballard 2000), as well as the improvement of dispatch information accuracy in emergency situations (Wilson et al. 1990).

However, the enhancement of HazMat emergency response capabilities has gained little attention when compared to other HazMat transport research issues in general, with the HazMat team locations problem in particular addressed very rarely. List and Turnquist (1998) stated that siting models in the hazardous materials area have mostly been applied to the problem of locating treatment or disposal facilities, the "obnoxious facility" problem. Conversely, the emergency response siting problem is relatively different and is more related to siting fire stations or emergency medical facilities.

To address the problem of insufficient emergency response coverage for rural remote areas, Saccomanno and Allen (1988) proposed a model for locating emergency response capability on a road network. The process is treated as a minimum set covering problem, in which a minimum acceptable level of response (maximum allowable response time) is assigned to all nodes on the network. Accordingly, their model was applied to the southwestern Ontario region.

Parentela and Sathisan (1998) presented a methodology for evaluating emergency preparedness for hazardous materials transportation. Emergency preparedness is measured in terms of response times, number of response units, and capabilities of initial responders. The analysis involves identification of emergency response units, their locations, determination of service zones, and evaluation of response capability. Results of the analysis permit development of strategies for allocation of resources, such as establishing locations for new response units, improving the capabilities of existing ones, and providing mobile stations at critical areas.

In some cases, research in the area of HazMat teams location is dedicated to the types of HazMat with unique characteristics. For example, research by List and Turnquist (1998) addressed the combined problem of routing and siting emergency response teams for high-level radioactive waste shipments and have formulated the combined routing-siting model as a multiobjective problem with three major elements: 1) identification of the nondominated routes for each origin-destination pair, 2) assignment of the flows to those routes to calculate link volumes; and 3) selection of emergency-response-team sites based on the assigned flows and other link characteristics. List and Turnquist constructed these models with the following objectives: 1) minimizing total shipment distance (truck miles), 2) minimizing total accident probability, 3) minimizing total population exposure, 4) minimizing the risk-and-volume weighted average response distance, and 5) minimizing the maximum response distance among all links.

Despite List (1993) acknowledgment of risk as a potential criterion for locating HazMat teams, the objective of his model was to minimize a generalized cost function, which is defined as the sum of weighted values of total response time, maximum response time, total risk, and maximum risk. The risk measure in that model was defined as the average number of injuries (total number of injuries/total exposed population). As a result, the model and its physical interpretation were not clear. Furthermore, the risk model resulted in a linear relationship between risk and response time (but a non-linear relationship was anticipated by List). The model was applied to an urban area with the results the same for the objective of minimizing average response time and minimizing average risk due to the risk model being linear in response time as well as the scaled risk measure.

2.4 Fire Station Location Problem

Although research on the HazMat team location is limited, research in locating emergency response units in general (fire station, ambulances, etc.) has gained greater attention. The fire station location problem has been extensively modeled as a Set Covering Location Problem (SCLP) with many variations. In the SCLP (Toregas et al. 1971 as cited in Aytug and Saydam 2002), the objective is to minimize the number of facility stations required to cover demand points within a specified response time. In the maximal covering location problem, MCLP (Church and ReVelle 1974 as cited in Aytug and Saydam 2002) the coverage constraint is relaxed by allowing some demand points not to be covered. Researchers have used minimum distance (Chen and Ren 2003), minimum response time (Erkut et al 2001), or both (Badri et al. 1998) as location criteria. An extensive survey of location covering problems is given in Schilling et al. (1993).

Most fire station location studies are primarily conducted for a certain urban area, such as the “Fire Station Location and Fire/Ambulance Study for City of Toronto’ (KPMG Canada 1999), the “City of Chattanooga Fire Department Management Study” (MTAS Consultants 1997), and the “Fire Station Location Study for the City of Melrose” (Firescope INC. 1996). However, these limitations are major concerns since these studies were restricted to a certain urban area and did not consider the regional aspect of emergency response coverage.

2.5 Location Models

The problem of locating emergency response units in general is frequently solved using location models and optimization techniques. Optimization is used to find the location that will minimize (or maximize) one (or more) objective function(s) under a set of constraints. Usually the basic objective is to assign emergency response units in a region so as to either maximize the covered areas or minimize the cost, time, or distance.

Location methods can be classified into location on a plane or location on a network. Also, location models could adopt a continuous (or spatial) approach, where all points on the plane or network are considered candidates for locations, or a discrete approach where only a set of points of the plane, or on links, are considered as location candidates.

The plane-based models tend to be used for urban areas and require substantial information regarding types of calls for service, responses times, population, land uses, and other variables. Network-based location models, conversely, have addressed urban issues, but they are also suitable to larger rural areas and warrant consideration in this vein.

Discrete Models are commonly used for locating emergency response facilities. The problem can be defined as follows: given a set of points $j = 1,\ldots, n_d$, representing the demand locations, and another set $i = 1,\ldots, n_f$, denoting the possible locations of facilities, determine the locations of n_p units among the candidate n_f locations at which the objective function is minimized (or maximized).

The choice of the objective function to optimize depends mainly on the definition of the facility location problem in concern. Objective functions for these type of problems may be represented by one of the following examples (Rushton 1979):

1. Minimizing total cost (distance/travel time) for a known number of facilities. This objective function considers efficiency of the system but does not consider equity of coverage for different demand points. Such a problem is called the P-median problem.
2. Minimizing maximum cost (distance/travel time) at nodes for a known number of facilities. In this case equity for different demand nodes is considered but not the efficiency of the system. This problem is known as the P-centre or MinMax problem.
3. Minimizing total cost (distance/travel time) on the network subject to a maximum cost (distance/travel time) constraint at each node for a known number of facilities. In this case both efficiency and equity are considered to some level. Trade-off curves could be obtained by varying the maximum acceptable cost level (Hansen et al. 1983). However, the solution might not be feasible under certain number of facilities-maximum cost combination.
4. Minimizing the number of facilities to be located so that each point on the network is within a critical cost (distance/travel time) value from the closest facility. In this case,

the number of facilities is seeked. This problem is known as a **set-covering** problem and considers equity among demand nodes.

5. Maximizing the number of nodes within a certain acceptable cost level given a known number of facilities. Such a problem is called a **Maximal covering** problem.
6. Multi-objective function where the different objective functions might be some combination of previously discussed objective functions, such as, minimizing total cost and minimizing maximum cost.

Much research has been done to provide enhancements to the aforementioned problems, such as consideration of multiple response units coverage (Batta and Mannur 1990), the stochastic nature of the problem (Berman et al. 1990) and the problem of server congestion (Desrochers, et al. 1996). However, researchers have mostly used minimum distance (Chen and Ren 2003), minimum response time (Erkut et al 2001), or both (Badri et al. 1998) as location optimization criteria. Conversely, providing services for areas with the largest populations is the main concern for planners. Thus, while "minimizing response time" and "maximizing population covered" are some of the criteria used to define the optimal solution, they do not consider all factors associated with the movement of HazMat.

2.6 Quantitative Risk Assessment

While planning HazMat emergency response, HazMat transport risks posed on nearby communities must be considered. Generally speaking, HazMat risk is a function of HazMat release frequencies and the consequent damages resulting from such releases.

The frequency of HazMat releases is a function of vehicular accident rates, breach of containment, release conditional probabilities, and traffic exposure in terms of HazMat traffic volumes. Consequent damage, on the other hand, is a function of the type of HazMat, amount and rate of released quantity, hazard area, exposure or response time, meteorological conditions, ignition probabilities, and exposed population (Center for Chemical Process Safety 1995). At the network level, HazMat risk is commonly expressed as the summation of risk over all likely accidents and possible damages for different HazMat types, transportation/accident scenarios and release locations.

Quantitative Risk Assessment (QRA) methods are commonly used to assess HazMat risk during transportation. A QRA consists of identifying the accidental events and combining the expected frequencies and consequences to obtain a proper risk measure while taking into account both the likelihood and the magnitude of the hazard. Ang et al. (1989) suggested the following three-stage framework for risk analysis in transportation:

1) Determine the probability of an undesirable event (an accident involving the release of a hazardous material).
2) Estimate the level of potential exposure, given the nature of the event.
3) Estimate the magnitude of consequences (fatalities, injuries and property damage) given the level of exposure.

These three stages produce one or more probability distributions, with the last two producing conditional distributions. In practice, the process is seldom carried all the way through (List et al. 1991). Frequently, the conditional probability distributions are ignored and the product of the probability of a release accident, and the extreme consequence of the accident, are used to estimate the risk. The extreme consequence is often represented by the potentially impacted population.

2.6.1 Methodologies Used in HazMat Transport Risk Assessment

Unlike fixed HazMat facilities in which HazMat types, sources, and accident location conditions are all known, HazMat transportation risk assessment is associated with a road network and contains an element of uncertainty in regards to the expected location and condition of the accident site. The common approach to transportation risk analysis is to divide the HazMat route into portions where different parameters can assume the same value. The average length of each route portion should be set according to the scope of the analysis and to the extent of accuracy and reliability of the available data. The smaller the portion, the greater the accuracy will be. However, this enhanced accuracy will lead to larger computational efforts.

The rarity of HazMat accidents makes calculating HazMat accident probabilities for each link difficult. General truck accident rates are sometimes used to estimate such probabilities. Furthermore, the characterization of the release scenarios with regard to escape rate and duration are usually based on scarce historical accident and release data, engineering judgment, and literature information, hence, different research uses different assumptions regarding the rate and amount of release (Spadoni, et al. 1995). Due to limited data on historical accidents and releases, release amounts and rates are usually highly uncertain.

For transportation QRA, the common practice is to draw a band of fixed width along each link and to use the number of people living within this band as the consequence measure (see ReVelle et al. 1991). This calculation assumes that all people within the band will be impacted equally and that no one outside of the band will be impacted at all. Yet, estimates made by drawing a band of fixed width along the road may be quite inaccurate because the probability of a consequence depends on the concentration of contaminant.

Rhyne (1994) and the Center for Chemical Process Safety (1995) explain quantitative transport risk analysis and how it can be applied to the surface transportation of hazardous material. Nicolet-Monnier and Gheorghe (1996) highlighted the main procedures for assessing the regional risks resulting from HazMat storage, and transportation by means of different systems (i.e., road, rail, ship, and pipeline).

An example of Transport QRA model development is the “Transport of Dangerous Goods through road tunnels Quantitative Risk Assessment Model” software package written by Institut National de l'Environnement et des Risques (France), WS Atkins (U.K), and The Institute of Risk Research, IRR, at the University of Waterloo (Ontario, Canada). It was first released in 1998 and the latest version with substantial enhancements was released in 2004.

Brown et al. (2001) detail a quantitative risk assessment process conducted for transportation of selected hazardous materials in the USA on a national basis. The final report entitled "A National Risk Assessment for Selected Hazardous Materials Transportation" is the result of a multi-year research effort sponsored by the US Office of Hazardous Materials Safety. The study objective was to provide an approximation of overall societal risk associated with the transportation of selected hazardous materials on national bases. The authors claim that their work is the first comprehensive application of these techniques in this arena for this purpose. However, in 1991 a similar study was conducted by the UK Health and Safety Executive (1991) to assess the national level of risk in the UK from different modes of HazMat transport.

2.6.2 Uncertainty in Risk Estimates

A major issue of concern in the process of HazMat quantitative risk assessment is the level of uncertainty associated with it. Analysts use detailed and sophisticated models to describe HazMat accidents; however, identifying all of the factors that may contribute to an accident is impossible. In many cases certain input data is imprecise. Furthermore, consequence models are often a mathematical approximation to limited experimental data (Arendt et al. 1989). Accordingly, many factors contribute to the level of uncertainty in QRA, including ambiguity in HazMat routing and volumes data, the under-reporting of the HazMat accidents and releases, and uncertainties in regards to conditions at the time and location of release.

Moreover, QRA models may give different results if different assumptions about release conditions and/or site conditions are used. Also, poor appreciation of input factors such as accident rates, travel time, traffic volumes, as well as population characteristics, are likely to result in a risk assessment insensitive to such factors. The end result is the over or under-estimation of risk levels.

Many analysts criticize the usage of absolute values of HazMat risk estimates in decision making processes. Rhyne (1994) argued that the accuracy of absolute risk results depends on whether all the significant risk contributors have been included, the realism of the models, and the uncertainty associated with the input data. However, the limitations of HazMat QRA become less significant in cases of comparing risk estimates among different alternatives. The US Environmental Protection Agency (1999) suggested that even under such uncertainty, QRA could be used for comparison purposes. For example, local emergency planning committees can use relative differences in risk estimates to aid in establishing chemical accident prevention and preparedness priorities among facilities in a community. In our opinion, despite such limitations, it is safe to assume that QRA can provide a rational basis for making decisions regarding comparing different alternatives for HazMat locations.

2.7 Summary

This chapter introduces a background and literature review on different issues related to HazMat transport and emergency response. The current practice as well as the academic research in locating HazMat teams was reviewed. The problem of locating fire stations and location models in general was discussed. Finally, an introduction to quantitative risk assessment was provided.

CHAPTER 3: RISK-BASED HAZMAT TEAM LOCATION OPTIMIZATION MODEL

This chapter presents a model for planning HazMat team locations specifically for handling HazMat transport accidents on a regional road network. Different from conventional methods, the proposed model adopts a risk-based optimization approach. Using risk as a location criterion accounts for not only population distribution, travel distance or response time, but also for many other risk-related factors including HazMat traffic volumes, HazMat routes, and release frequencies.

This approach provides a practical platform for evaluating the trade-offs between system costs (in terms of the number of fatalities), total network risk and individual node risk, and response time. The proposed model can be used to assess the current location of HazMat teams in a region and the risk implications associated with their placements. Furthermore, the model can help investigate how HazMat team locations can be tailored to recognize the risk of transporting HazMat and will provide a more objective set of input alternatives into the multi-criteria decision making process of regionally locating HazMat teams.

3.1 Road Network Representation

The HazMat transport-related accidents and the demand for HazMat emergency response services can occur at any point on the road network. However, considering all possible accident locations is both time and resource consuming, not to mention practically unachievable. Thus, to simplify the formulation of the problem, the continuous demand for HazMat emergency response services on links is substituted with a discrete set of demand nodes (a network node that represents a small part of the network to which HazMat emergency service must be delivered). Without loss of generality, we assume that both populations and highway activities (accidents) can be aggregated to such individual nodes, with each node representing, as much as possible, a homogeneous zone around it. Also, the assumptions stands that HazMat teams would only be assigned to a pre-defined set of nodes, representing current locations of fire stations, with no locations permitted on links. Network links serve only as connections between nodes and have been assigned appropriate travel times.

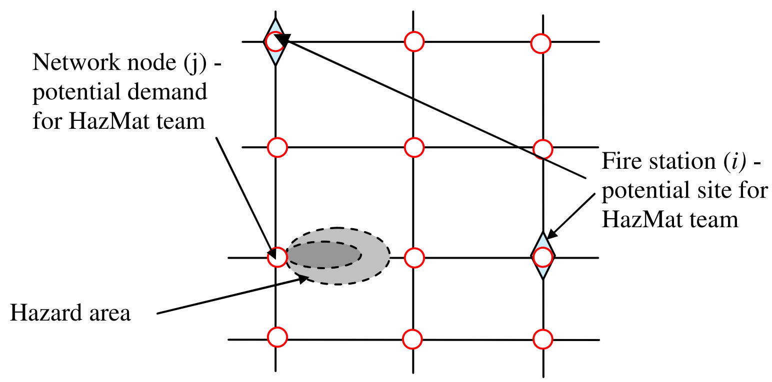


Figure 3-1: Schematic of highway network and HazMat team locations

Consider a regional highway network as shown in Figure 3-1. The road network is represented as a directed graph with nodes and links, G (N, A), where N is a set of network nodes, $N = \{j, j = 1,2,3,..., n_d\}$ and A is a set of network links, $A = \{l, l = 1,2,3,..., n_m\}$. The nodes represent population centers as well as highway intersections and intermediate points on long links. All network nodes, n_d, are considered potential demand nodes that may experience a HazMat accident-induced release. The released material escapes to the surrounding environment forming a hazard area. Within the hazard area there are different levels of HazMat concentrations, starting with the highest concentration near the release node and decreasing outwards. Populations within this hazard area will experience varying degrees of health impacts, ranging from negligible injury to death.

Over the network, there exists a set of n_f HazMat team candidate locations, denoted by F, where $F = \{i, i = 1,2,3,..., n_f\}$. The HazMat team candidate locations are assumed to exist only on a subset of network nodes (i.e., F $\subset$ N), with these HazMat team candidate locations designated as the *only* sites that can host a HazMat team. From the n_f candidate locations, only n_p HazMat teams are actually located on the network. The set of n_p HazMat teams is denoted by H, where $H = \{k, k = 1,2,3,..., n_p\}$. The relationship among different sets is as follows: H $\subset$ F $\subset$ N.

3.2 The Model

The HazMat team location model consists of two components: a Time-Dependant Quantitative Risk Assessment (TDQRA) module that estimates the risks for the network and at its specific nodes depending on response time to each node, and a location optimization module for locating HazMat teams on the network based on the risk involved (Figure 3-2).

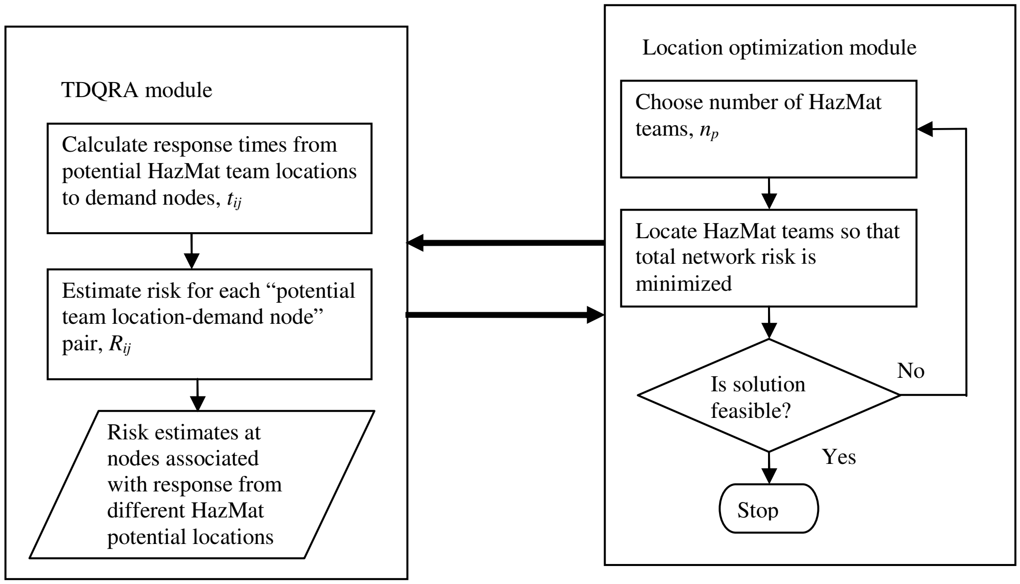


Figure 3-2: Model framework for locating HazMat teams.

The risk assessment module that forms the basis of the HazMat team location model is time-dependent. There is a specific response time, t_{ij}, from each candidate HazMat team location node *i* to each demand node *j*. In case of a HazMat accident, response time t_{ij} affects the level of risk at the accident scene *j*. In general, the longer it takes for the HazMat team to reach an accident location, the more severe the consequences will be.

The HazMat accident risk at node *j* associated with an emergency response from HazMat team at node *i* with response time t_{ij}, is denoted by R_{ij}. The risk set for all "demand node-candidate response location" combinations is defined as:

$$R = \{R_{ij}; i = 1,2,3,\ldots,nf; j = 1,2,3,\ldots,nd\} \tag{3-1}$$

Response to a demand node j will be from the nearest candidate node i that actually hosts a HazMat team, hence, risk at node j is defined as:

$$R_j = \min_i (R_{ij}), \ \forall i \in H \tag{3-2}$$

The TDQRA technique is proposed to estimate the risk set, R, and hence the total network risk associated with different HazMat team location strategies.

The HazMat team location problem involves locating a given number of HazMat teams, n_p, at pre-defined n_f candidate locations to meet the demand for emergency service resulting from HazMat accidents at different network nodes. There are C(n_p, n_f) possible solutions, with each HazMat team to provide emergency response to a certain number of nearby nodes for each location solution. Different location solutions of n_p HazMat teams on the network result in different response times, hence, different risk levels for the network nodes. The location optimization module uses risk estimates , R_{ij}, from the TDQRA module to find the best HazMat team location set, H, that would minimize total network risk while assuring response time at different nodes is within a minimum acceptable threshold. The problem is formulated as a multi-facility location problem on a network, with the module framework given in Figure 3-2.

The proposed model recognizes the importance of minimizing the total risk on the network and at the same time the need to maintain a minimum acceptable level of service for all nodes to ensure a minimum level of equity among all communities. This balance is accomplished by establishing minimum acceptable level of service at remote locations regardless of lower levels of population concentration. If few people live at the marginal nodes, risk will be low and these nodes will likely not receive HazMat response service under the total risk minimization objective. However, the maximum response time threshold constraint overcomes this problem by considering response time, thus allowing marginal nodes to receive a minimum coverage despite lack of population.

This approach has the advantage of finding the most efficient solution by minimizing the total risk on the network (maximum savings) while accounting for a maximum acceptable response time for all nodes. On the other hand, a clear definition of the maximum acceptable level of risk and response time at nodes is required—a figure which might not be easy to determine.

The suitable number of HazMat teams to be located is yet unknown and needs to be determined iteratively. However, this problem may not be feasible under a certain number of HazMat teams and the maximum acceptable response time, T_{max}. Basically, if too few HazMat teams exist, providing acceptable service to all marginal locations becomes difficult. The minimum number of HazMat teams required to maintain the minimum level of service can be obtained through the following iterative steps:

1. Calculate the response time t_{ij}, using the shortest response time from each candidate location node, i, to each demand network node, j.
2. Calculate the risk, R_{ij}, from each candidate location node, i, to each demand node, j, using previously calculated response times.
3. Assume n_p HazMat teams.

4. Using R_{ij} locate n_p HazMat teams among HazMat teams candidate locations, n_f, so as to minimize total network risk while assuring response time at different nodes is within a minimum acceptable threshold.
5. If solution is feasible, stop, otherwise increase n_p and go to step 4.

The model with its two modules is developed as a Windows-based user-friendly software that allows HazMat emergency response planners to investigate different emergency response policies. A user manual for the software is given in Appendix D.

3.3 The Time-Dependant Quantitative Risk Assessment (TDQRA) Module

This section introduces the Time-Dependant Quantitative Risk Assessment (TDQRA) module that quantitatively assesses the risks of HazMat road transport with the consideration of emergency response to HazMat accidents. Although the bases of risk assessment analysis allows for the time element to be considered, it is a common practice in traditional QRA techniques to assume the worst case scenario (or other alternative scenario) in order to keep analysis in a practical range (US Environmental Protection Agency 1999). In the proposed TDQRA, a more realistic approach is used where risk estimates will vary for different locations of HazMat teams depending on associated response time. HazMat release is assumed to continue until a response occurs from the nearest team location.

HazMat team response time is a function of various factors including, but not limited to, the distance between the team locations and accident sites, the layout of the region, weather conditions, road and traffic conditions, notification and dispatch time. Fire departments have used two different methods to calculate response time, with many departments adopting the Office of the Fire Marshal method. This procedure is defined as "the elapsed time between receipt of the call by the department and the arrival of the first unit at the occurrence location." Other parties, such as NFPA, have adopted "response travel time" which is considered to be the time that begins when units are en route to the emergency incident and ends when units arrive at the scene.

This research adopts a response time definition that differs from the previous two. We defined response time as the time elapsing from the release occurrence until mitigation measures are applied at the release scene. Following this definition, response time has three components: dispatch time at the station, travel time from the station to the site, and mitigation time (time to apply mitigation measures at the site, mainly containment and evacuation). Response time from the nearest HazMat team to the release location is calculated using a “fastest route” algorithm, based on the label-correcting shortest path algorithm (Abuja et al. 1993).

The risk estimates for HazMat releases can account for short-term health effects (i.e. fatalities and injuries), containment and decontamination expenses, environmental damage and rehabilitation expenses, or long-term heath problems. QRA models usually use the number of fatalities and/or injuries as a measure of risk, assuming that other consequences will be proportional to fatalities and injuries (Organization for Economic Co-operation and Development 2004, UK Health and Safety Executive 1991). In the proposed TDQRA module, estimated number of fatalities will be used as a risk measure; however, the impact on the environment in the vicinity of release will also be investigated.

In this research a regional societal risk measure is used (Nicolet-Monnier & Gheorghe 1996). Regional societal risk is defined as the expectation of fatalities that result from the transportation of different types of HazMat on the road network of a region. Regional societal risk is expressed as the summation of risk over all likely accidents and possible damages for different HazMat types, transportation/accident scenarios and release locations.

The proposed TDQRA includes the following principal considerations in modeling HazMat transportation risk:

1) Within the scope of this research we are only interested in transport related accident-induced risk. Non-transport related or non-accident related releases are not considered in this research.
2) We adopted a discrete node system instead of a link-based approach frequently used in HazMat transport risk assessment.
3) Risk estimates depend directly on time elapsing until mitigation takes place. The frequency aspect of HazMat release does not depend on release time; however, the consequence part is directly related to it. Longer release times result in larger

quantities released, higher concentrations of hazardous substances in the vicinity of the release, longer exposure times for toxic materials, and higher ignition probabilities for flammable materials.

4) Frequencies of release scenarios are to be estimated at the selected potential release nodes by aggregating release frequencies over the links to the nearest potential release location. Moreover, the selection of representative potential release nodes and the level of aggregation will have an effect on the risk estimate. Thus, careful choice of the level of aggregation will result in better risk estimates.
5) Consequence estimates at the selected potential release nodes are carried out in a way similar to fixed facility risk assessment models with the fundamental difference of considering the response time effect on severity of damage to the nearby population.

3.3.1 Formulation of Risk Expression for HazMat transport

Consider a network with potential HazMat team locations as shown in Figure 3-1. For different types of HazMat, *k*, and different types of releases, *r*, each (*k,r*) pair represents a different release scenario. For a given HazMat type, *k*, the frequency of release of type *r* at node *j* is given by Frq_j^{kr}. Csq_{ij}^{kr} denotes the number of fatalities at node *j* that would result from release scenario (*k,r*) when the nearest HazMat team located at node *i* responds to the release. The two risk components are combined to calculate R_{ij}^{kr}, the expectation of fatalities at node *j* from a release type *r* of HazMat type *k* when response is provided by a HazMat team at node *i*, such that:

$$R_{ij}^{kr} = Frq_j^{kr} * Csq_{ij}^{kr} \tag{3-3}$$

Note that, Frq_j^{kr} depends only on the node location, *j*, but not on HazMat team locations. In contrast, Csq_{ij}^{kr} depends on response time and, hence, on both node location *j* and HazMat team location *i*.

The risk estimate from equation (3-4) is combined for all types of HazMat and release scenarios, *(k, r)*, to yield the total risk at location *j* where the nearest HazMat team is located at *i*, such that:

$$R_{ij} = \sum_k \sum_r R_{ij}^{kr} \tag{3-4}$$

Release frequency, Frq_j^{kr}, can be estimated either by statistical prediction models or from analysis of historical HazMat accidents and release trends. Similarly, consequences, Csq_{ij}^{kr}, can be determined using certain consequence models, depending on incident scenarios. Note that both frequency and consequences in Equation (3-3) depend on HazMat type *k* and release type *r*. Detailed calculations of Frq_j^{kr} and Csq_{ij}^{kr} are discussed in Chapter 4 and Chapter 5 respectively.

To restrict our analysis to points of major significance, the following assumptions are introduced in the proposed TDQRA:

- A limited number of representative HazMat;
- A limited number of release scenarios (release rates, release sizes, release outcomes);

- HazMat release consequent damage for off-road population only is considered ; and
- Limited weather conditions.

3.3.2 Choosing Representative HazMat Types (*k*)

To quantitatively assess the risk of HazMat movements, identifying and defining typical accidental release scenarios are needed. In Canada, there are more than 3000 regulated HazMat classified into 9 major classes (Transport Canada 1992). A full consideration of all HazMat types is time consuming and impractical. However, HazMat may be classified into major classes of substances for which quantitative risk assessments are feasible. The TDQRA module was limited to HazMat types that are transported in significant amounts and represent a large proportion of the overall HazMat traffic, i.e. flammable liquids (Button 1999), and those are considered to be potentially the most hazardous as confirmed by historical analysis, i.e. toxic liquefied gases, and flammable liquefied gases (Fewtrell and Siddique 1998). Toxic and corrosive liquids were also considered for their potentially high impact on the environment, although we assumed that these substances had no impact on the population. Other classes of HazMat are usually transported in smaller amounts or pose little risk to the nearby population.

Furthermore, specific HazMat were chosen to represent other similar hazardous materials in the same category: Gasoline to represent flammable liquids, Propane to represent flammable liquefied gases, and Ammonia to represent toxic liquefied gases.

At atmospheric pressure and temperature, Ammonia, Propane, and other LPG exist in a gas state. However, they are usually transported at atmospheric temperature but liquefied under pressure, thus making a release likely to result in the formation of a gas cloud based on the vaporization of much or all of the liquid. Concentration levels at different locations could be calculated using gas dispersion models.

Propane is an extremely flammable substance that is easily ignited by heat, sparks, or flames, and can form explosive mixtures with air. The vapors from liquefied gas are initially heavier than air and spread along ground. Additionally, vapors may travel to the source of ignition and flash back thus causing the original container to explode. Emergency response measures for Propane release include eliminating ignition sources, stopping leaks if possible, positioning leaking containers so that only gas escapes rather than liquid, using water spray to reduce vapors or to divert vapor cloud drift, and preventing the spread of vapors through sewers, ventilation systems, and confined areas (Transport Canada et al. 2000).

Ammonia is a toxic substance that may be fatal if inhaled. Emergency response measures for Ammonia release are similar to Propane, including stopping leaks if possible, turning leaking containers so that only gas escapes rather than liquid, preventing entry into waterways, sewers, basements or confined areas, and using water spray to reduce vapors or divert vapor cloud drift (Transport Canada et al. 2000).

Although Propane and Ammonia have different consequence damage, they both have the same release and dispersion mechanism, resulting in a dense gas cloud formation that is heavier than air. The behavior of dense gas clouds depends mainly on the released material, the nature of the release, and meteorological conditions.

According to the type of release, Britter and Griffiths (1982) classified the formation of dense gas clouds as 1) instantaneous: as in the catastrophic failure of a container, 2) continuous: such as a release through a small hole in the container, and 3) a combination of these two extremes: such as in the spillage of liquid transported at low temperatures onto land, in which case there will be an initial rapid boiling off followed by a more steady evolution of vapor. The overall effect of the release is a rapid formation of a dense cloud with the concentration varying according to the distance from the source. Concentrations are normally higher near the source and become lower as the gas disperses with distance.

For Ammonia and Propane releases, air movements can move, disperse, or trap the vapor cloud. Wind speed and atmospheric stability, are the primary meteorological conditions that influence dispersion or direction of the cloud. Other factors include ground roughness, and temperature inversions (US Environmental Protection Agency and National Oceanic and Atmospheric Administration 1999).

Gasoline is a highly flammable substance that is easily ignited by heat, sparks or flames. Gasoline is usually transported at atmospheric temperature and pressure.

Although below its boiling point, when Gasoline is released the liquid partially evaporates forming a flammable cloud above the released surface. Depending on the atmospheric conditions, the cloud might spread in the downwind direction to the source of ignition and flash back. Emergency response measures for Gasoline release include eliminating ignition sources, stopping leak if possible, preventing entry into waterways, sewers, basements or confined areas, use of vapor suppressing foam or water spray to reduce vapors, absorbing or covering released material with dry earth, sand or other non-combustible material, and transfer to containers. Also, dikes might be used for large spills.

Depending on the HazMat type, each release has a distinctive impact and associated consequence formulation. The liquefied toxic gases, represented by Ammonia, are the most difficult to model and affect the largest area. Moreover, though flammable clouds are no longer dangerous when diluted to about 2% by volume, toxic clouds may be dangerous even at very low concentrations. Thus, under equal release conditions, toxic clouds may be dangerous at much greater distances than flammable clouds. In case of flammable liquids, the distance to the endpoint is relatively small compared to other HazMat types.

3.3.3 HazMat Release Scenarios (*r*)

When considering release scenarios, releases are classified into two types—namely spill and leak—according to their duration (Transport Dangerous Goods Directorate 2004). Dangerous Goods Accident Information System (DGAIS) identifies *spill* as a release of short duration, while *leak* is a release of long duration. Unfortunately "short duration" and "long duration" were not defined in the DGAIS and no time value is given for the terms. Furthermore, the respective release types "spill" and "leak" are additionally classified into high and low release according to the amount released. Large release is defined as release over 1000 liters, while a small release is a release less than or equal to 1000 liters.

3.3.4 Summary of Considered HazMat Types and Release Scenarios

In this research, the following four representative HazMat types (*k*) are considered:

1. Toxic liquefied gases (Ammonia)
2. Flammable liquefied gases (Propane)
3. Flammable liquids (Gasoline)
4. Toxic/corrosive liquids

The release types (*r*) are classified into,

1. Large spill
2. Small spill
3. Large leak
4. Small leak

With four HazMat types and four release types, there are a total of 16 release scenarios as shown in Table 3-1. These release scenarios are similar to those proposed by Sacconanno et. al. (1998).

Table 3-1: Release scenarios

Release scenario	HazMat type (k)	Release type (r)	Frequency at j	Consequence at j for a response from HazMat team at i	Risk at j for a response from HazMat team at i
1	1. Ammonia	1. Large spill	$Frq_j^{1,1}$	$Csq_{ij}^{1,1}$	$R_{ij}^{1,1}$
2	1. Ammonia	2. Small spill	$Frq_j^{1,2}$	$Csq_{ij}^{1,2}$	$R_{ij}^{1,2}$
3	1. Ammonia	3. Large leak	$Frq_j^{1,3}$	$Csq_{ij}^{1,3}$	$R_{ij}^{1,3}$
4	1. Ammonia	4. Small leak	$Frq_j^{1,4}$	$Csq_{ij}^{1,4}$	$R_{ij}^{1,4}$
5	2. Propane	1. Large spill	$Frq_j^{2,1}$	$Csq_{ij}^{2,1}$	$R_{ij}^{2,1}$
6	2. Propane	2. Small spill	$Frq_j^{2,2}$	$Csq_{ij}^{2,2}$	$R_{ij}^{2,2}$
7	2. Propane	3. Large leak	$Frq_j^{2,3}$	$Csq_{ij}^{2,3}$	$R_{ij}^{2,3}$
8	2. Propane	4. Small leak	$Frq_j^{2,4}$	$Csq_{ij}^{2,4}$	$R_{ij}^{2,4}$
9	3. Gasoline	1. Large spill	$Frq_j^{3,1}$	$Csq_{ij}^{3,1}$	$R_{ij}^{3,1}$
10	3. Gasoline	2. Small spill	$Frq_j^{3,2}$	$Csq_{ij}^{3,2}$	$R_{ij}^{3,2}$
11	3. Gasoline	3. Large leak	$Frq_j^{3,3}$	$Csq_{ij}^{3,3}$	$R_{ij}^{3,3}$
12	3. Gasoline	4. Small leak	$Frq_j^{3,4}$	$Csq_{ij}^{3,4}$	$R_{ij}^{3,4}$
13	4. Toxic liquids	1. Large spill	$Frq_j^{4,1}$	$Csq_{ij}^{4,1}$	$R_{ij}^{4,1}$
14	4. Toxic liquids	2. Small spill	$Frq_j^{4,2}$	$Csq_{ij}^{4,2}$	$R_{ij}^{4,2}$
15	4. Toxic liquids	3. Large leak	$Frq_j^{4,3}$	$Csq_{ij}^{4,3}$	$R_{ij}^{4,3}$
16	4. Toxic liquids	4. Small leak	$Frq_j^{4,4}$	$Csq_{ij}^{4,4}$	$R_{ij}^{4,4}$
		Total risk at j for a response from HazMat team at i, $R_{ij} =$			$\sum_{k=1}^{4}\sum_{r=1}^{4} R_{ij}^{kr}$

3.3.5 Release Amounts and Discharge Rates

For this research, the DGAIS data (Transport Dangerous Goods Directorate 2000) for the years 1988 to 2000 was used to identify default values for discharge rates of different releases scenarios. The DGAIS is a database maintained by Transport Dangerous Goods Directorate, Transport Canada and consists of all reported[2] accidents

[2] A report is filed if the accident involving a dangerous good results in a release that presents a danger to health, life, property, or the environment. Reports are also filed for accidents involving death or injury, or damage to the means of containment.

involving the transport of HazMat. The data is presented on an annual basis and is available for the years 1988 to 2000.

DGAIS accident records from trucks in transit on roads were used for this study, with accident records for truck that are loading, unloading or in storage not considered. The database includes approximately 1,800 relevant HazMat accident records. Numbers of relevant reported accidents for each HazMat type are as follows: 1044 flammable liquids, 655 toxic/corrosive liquids, 69 flammable liquefied gases, and 32 toxic liquefied gases. Table 3-2 lists number and percentage of relevant releases reported by DGAIS as well as their percentage for each of the assumed release scenarios.

Table 3-2: DGAIS number and percentage of relevant releases for different HazMat and release types

		Small spill	Large spill	Small leak	Large leak
Flammable liquids	# of releases	331	525	149	39
	%	32%	50%	14%	4%
Toxic/corrosive liquids	# of releases	316	83	240	16
	%	48%	13%	37%	2%
Flammable gases	# of releases	6	15	28	20
	%	9%	22%	41%	29%
Toxic gases	# of releases	3	5	17	7
	%	9%	16%	53%	22%

A high level of detail is available for each accident, ranging from the date, time, and location of the accident to the emergency response personnel who responded to the scene of the accident. Moreover, the database consists of 3 files—Accident, Commodity, and Comment. Additionally, relevant DGAIS data fields include:

- SHIPNAME: The shipping category (type) for the HazMat, e.g. Gasoline, Propane, Anhydrous Ammonia.
- CLASS: The class assigned to each HazMat.
- MODE: The mode of transport and whether the accident occurred on transit or not.
- TYPE: Whether an accident involved a spill, leak, fire or explosion.
- VEHICLE: The type of vehicle involved.
- DGLMASVOL: The mass/volume released from the shipment.

Table 3-3 shows the minimum, maximum, and average release values for the four types of HazMat. The observed maximum release amounts are consistent with a maximum truck capacity of 63.5 ton (total weight) set by the Canadian standard (Ministry of Transportation of Ontario, Carrier Safety and Enforcement Branch 2001) as well as a report[3] from "Shell Canada" in regards to their tanker truck loads. However, in the UK, the Health and Safety Executive (1991) reported very different tank capacities for the different types of HazMat, as stated in Table 3-4. It should be noted that, when using a TDQRA module to evaluate HazMat transportation risks for countries other than Canada, some modifications might be needed to account for different discharge rates and amounts.

[3] Email communication

Table 3-3: Minimum, maximum and average amounts for HazMat releases

HazMat type	Release amount (Kg)		
	Minimum	Maximum	Average
Flammable liquids	0.75	45,450	5,483
Toxic/corrosive liquids	1	47,000	1,572
Flammable liquefied gases	0.51	33,303	5,544
Toxic liquefied gases	0.64	16,440	1,676

Table 3-4: UK Health and Safety Executive assumptions for tank capacity for HazMat transport

HazMat type	Representative substance	Tank capacities (ton)
Liquefied flammable gases	Propane	15
Liquefied toxic gases	Ammonia	15
Flammable liquids	Gasoline	20-25

Figure 3-3, Figure 3-4, Figure 3-5 and Figure 3-6 show the cumulative distribution of HazMat released amount for flammable liquefied gases, toxic liquefied gases, flammable liquids, and toxic liquids, respectively as reported by DGAIS. As expected, HazMat releases follow a distribution and are not limited to discrete categories. A study by Button (1998) used the DGAIS data as a primary source of information to estimate the probabilities of release for the presented 16 release scenarios in case of a truck accident with and/or without overturns and collisions.

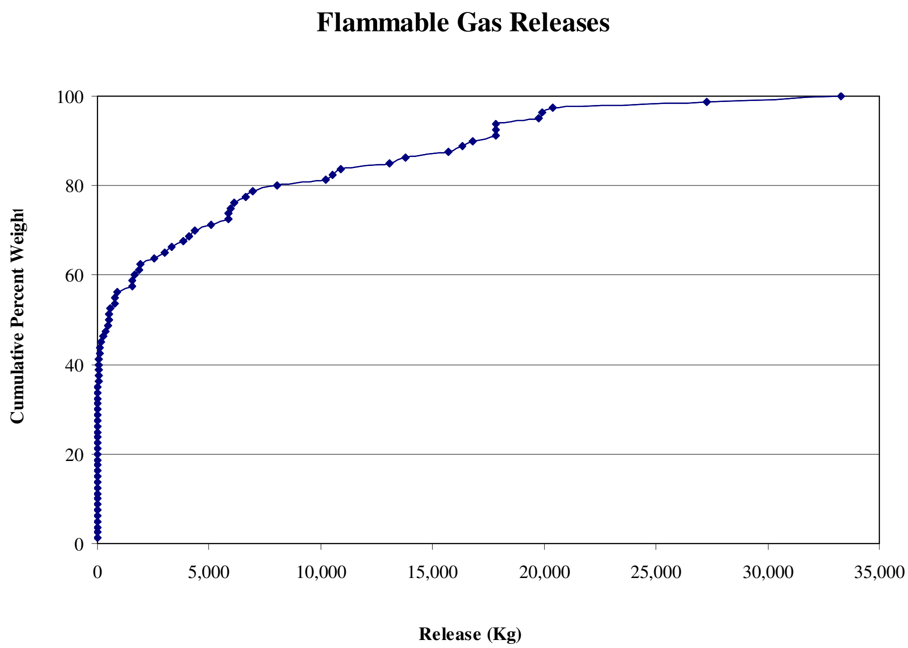


Figure 3-3: Cumulative distribution of flammable liquefied gases accident induced releases

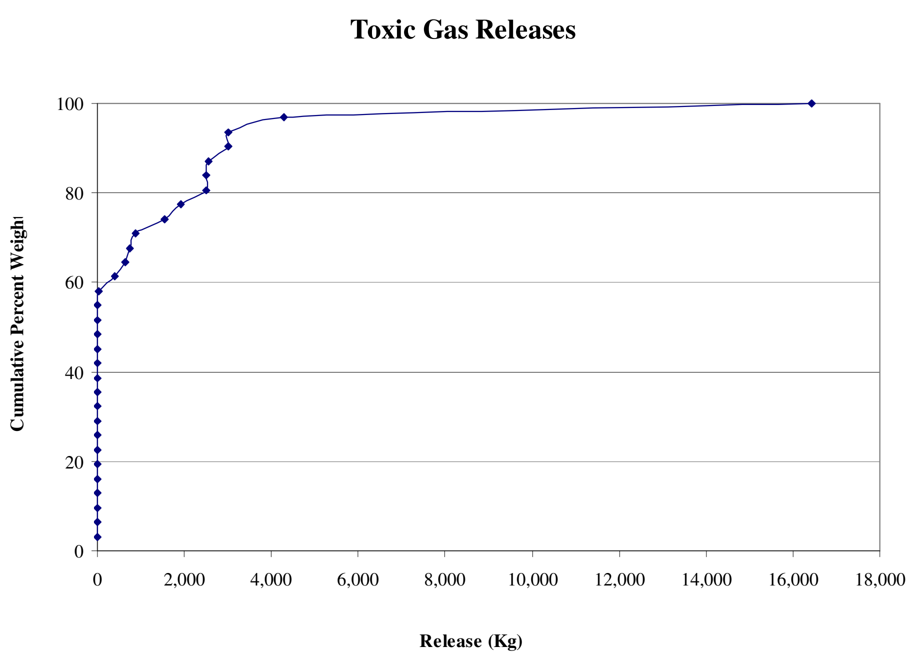


Figure 3-4: Cumulative distribution of toxic liquefied gases accident induced releases

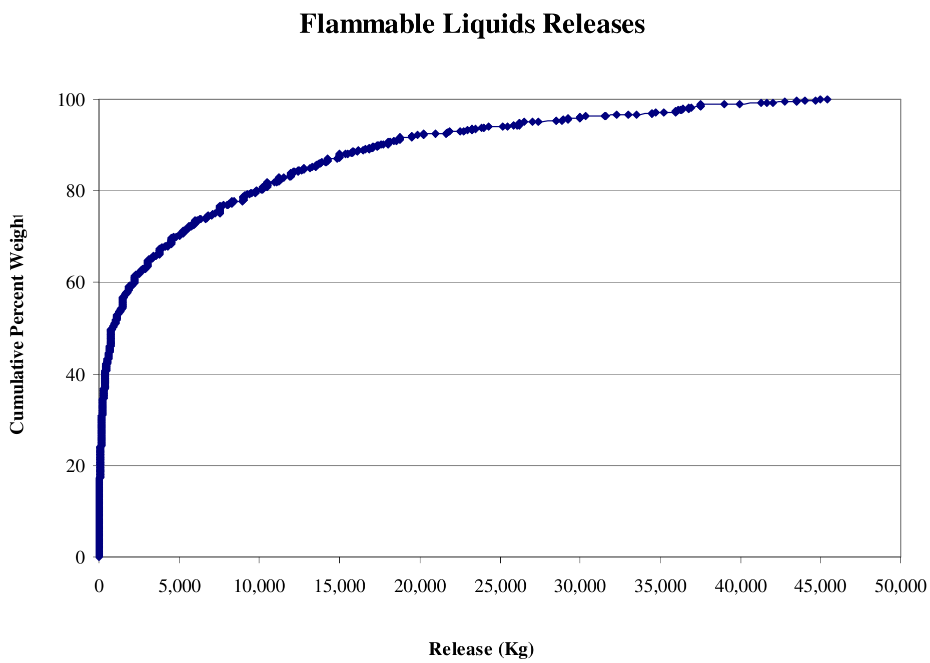


Figure 3-5: Cumulative distribution of flammable liquids accident induced releases

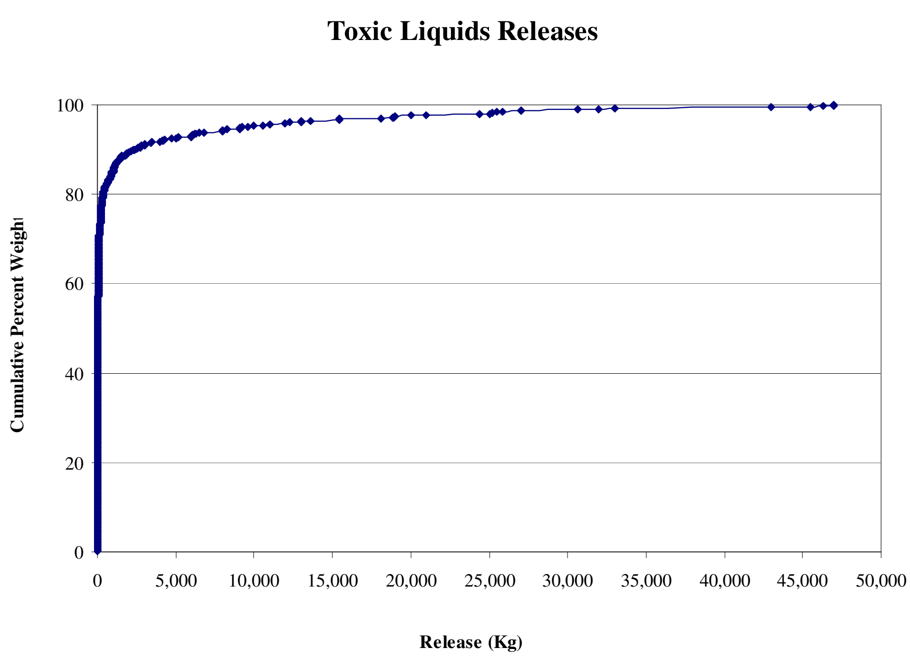


Figure 3-6: Cumulative distribution of toxic/corrosive liquids accident induced releases

For the DGAIS data, the classification of release into "large" and "small" covers a wide range of released amount. The average values of the total amount released are used to estimate discharge rates for the four types of HazMat with the average released amount for different release scenarios presented in Table 3-5. Furthermore, an assumed average spill duration of 15 minutes and average leak duration of 60 minutes are used to calculate different discharge rates. Table 3-6 lists estimated discharge rates for different release scenarios.

Table 3-5: Average release amounts[4] (kg) by HazMat type and release type

	Average release amount (kg)			
	Flammable LPG	Toxic LPG	Flammable liquids	Toxic/corrosive liquids
Ave small spill	71	136	192	94
Ave large spill	9680	5039	9388	10757
Ave small leak	36	3.4	112	56
Ave large leak	7259	2113	5531	5891

Table 3-6: Discharge rate for different scenarios (kg/min)

	Discharge rate (kg/min)				
	Flammable LPG	Toxic LPG	Flammable liquids	Toxic/corrosi ve liquids	average release duration (min)
Ave small spill	4.7	9	12.7	6.3	15
Ave large spill	645.3	336	626	717.1	15
Ave small leak	0.6	0.06	1.9	0.9	60
Ave large leak	121	35	92	98.2	60

[4] These estimates are based on the DGAIS data and the definition of small release <1000 liter and large release > 1000 liter

The HazMat releases for different scenarios are modeled as a constant discharge rate for the whole duration of the release; yet this might not be accurate since release usually begins at a high rate only to taper off with the reduction of the amount of HazMat material in the tanker. However, the adopted fixed discharge rates would be good enough and consistent with the level of analysis details through out the module.

3.4 The Location Optimization Module

In the proposed location optimization module, the objective is to find the optimal location of the n_p HazMat teams among the n_f possible candidate nodes so as to minimize the total network risk using the R_{ij} estimates from the TDQRA module. At the same time, we ensure that response times to any marginal nodes do not exceed some pre-set threshold (T_{max}).

The nearest HazMat team located at node *i* is assumed to respond to the release at node *j* in a time equal to response time t_{ij}. For each node *j*, we introduce a set of candidate HazMat team locations, N_j, that fulfills the maximum response time restriction, that is:

$$N_j = \{i; T_{ij} \leq T_{\max}\} \tag{3-5}$$

For a given location solution of the n_p HazMat teams on the network, a unique measure of total network risk over all nodes is defined as follows:

$$R = \sum_j \sum_i R_{ij} * z_{ij} \tag{3-6}$$

Where z_{ij} is a decision variable that equals 1 if node *j* is covered with HazMat team at node *i*; and zero otherwise.

The location problem of our interest can now be formally stated as,

$$Min \quad R = \sum_j \sum_i R_{ij} * z_{ij} \qquad \textbf{(3-7)}$$

Subject to:

$z_{ij} = \begin{cases} 1 \\ 0 \end{cases}$	if node *j* covered by HazMat team at *i* otherwise	**(3-8)**
$N_j = \{i; t_{ij} \leq T_{\max}\}$		**(3-9)**
$\sum_{i \in N_j} z_{ij} = 1$	node *j* must be covered with one location within N_j set	**(3-10)**
$y_i = \begin{cases} 1 \\ 0 \end{cases}$	if a HazMat team exists at *i* otherwise	**(3-11)**
$0 \leq z_{ij} \leq y_i$	no coverage from *i* to *j* unless a HazMat team is located at *i*	**(3-12)**
$\sum_i y_i = np$	total number of HazMat teams to be located $= n_p$	**(3-13)**

In the objective function **(3-7)**, the summation over *j* ensures that total risk is minimized over all demand nodes *j*. The second summation over *i* ensures that risk at any demand node *j* is minimized over all neighboring teams *i*.

It should be noted that for a given demand node j, minimizing risk over i means response will be from the nearest unit, since response time is the only risk variable that depends on the location i. Constraint **(3-10)** ensures that every demand node j is covered by one team within the allowable response time thresholds. Constraint **(3-12)** ensures that no response will be initiated from i unless a HazMat team exists at i. Constraint **(3-13)** ensures that the number of teams located equals n_p.

The optimization problem could be further simplified by pre-processing the input risk estimates, with the maximum response time constraint achieved by assigning a large value "M" for R_{ij}'s that does not satisfy the T_{max} constraint. In this case, constraint **(3-9)** is eliminated and the summation in constraint **(3-10)** would be over all i's.

The problem belongs to the category of NP hard problems, which means that no exact polynomial algorithm is yet known to solve this type of problem. Thus, an optimal solution could only be obtained through algorithms with exponential execution times. These algorithms are convenient for small problems, but they are inefficient, and practically useless, for larger problems. Heuristic algorithms are commonly used to reach a reasonable near-optimal solution for large problems; however, the HazMat location problem is relatively small since candidate locations are limited to a pre-defined set of nodes representing current fire station locations. The restriction of HazMat team locations to a pre-defined set of nodes (n_f) limits the size of the optimization problem, where the number of decision variables for z_{ij} equals $n_f * n_d$, and the number of decision variables for y_i equals the n_f variable. Moreover, the problem could be solved using complete enumeration. Other heuristic algorithms to solve the problem include neighborhood search, branch and bound, and Lagrangian relaxation techniques.

Chapter 6 illustrates the application of this module and the associated solution method using the southwestern Ontario region. The problem we are interested in is expected to be relatively small since the number of potential locations is limited to the existing fire stations; therefore a solution will be found using complete enumeration.

3.5 Summary

This chapter introduced the risk-based HazMat team location optimization model with its two components: the time-dependant quantitative risk assessment module (TDQRA) and the location optimization model. Four representative types of HazMat are considered, namely: toxic liquefied gases (represented by Ammonia), flammable liquefied gases (represented by Propane), flammable liquids (represented by Gasoline), and toxic/corrosive liquids. Four release scenarios are presented (large spill, small spill, large leak, and small leak) and correspondent discharge amounts and rates are estimated. Detailed calculations of frequency and consequence estimates are discussed in Chapter 4 and Chapter 5, while the application of the model is illustrated in Chapter 6 through a southwestern Ontario case study. The model with its two modules is developed as a Windows-based user-friendly software that allows HazMat emergency response planners to investigate different emergency response policies. A user manual for the software is given in Appendix D.

CHAPTER 4: ANALYSIS OF HAZMAT RELEASE FREQUENCY

A major component in the TDQRA module discussed in the previous chapter is the frequency calculation of different release scenarios. In developing the TDQRA, only accident induced releases are considered since they dominate the risk of HazMat transport (Center for Chemical Process Safety 1995). The purpose of this chapter is to determine the accident induced release frequencies for the 16 release scenarios described previously (Frq_j^{kr} in Table 3-1).

4.1 Estimation of Release Frequencies

In traditional QRA analysis, the transportation network is represented by a set of links with related transport attribute estimates. However, in the proposed TDQRA module, a discrete approach is used where release frequencies are estimated at nodes. The release frequencies are first estimated on links in the same way as traditional transportation risk assessment techniques. Then, link release frequencies are aggregated to adjacent nodes. At node j, frequency of release of type r for a given HazMat type k, Frq_j^{kr}, is calculated by summing half of release frequencies on all adjacent links according to the following equation:

$$Frq_j^{kr} = \sum_l 0.5 * Frq_l^{kr} \quad \text{for all links } l \text{ adjacent to node } j \qquad \textbf{(4-1)}$$

Here Frq_l^{kr} is the annual frequency of occurrence by particular release *r*, of a given type of HazMat *k*, on a given link *l*. Frq_l^{kr} is estimated by combining the annual rate of trucks carrying HazMat being involved in an accident, the annual rate of a specified release scenario (*kr*) taking place given an accident, and the annual traffic volume of a given type of HazMat (*k*) on a given link (*l*). Figure 4-1 shows the process for estimating release frequencies for different release scenarios.

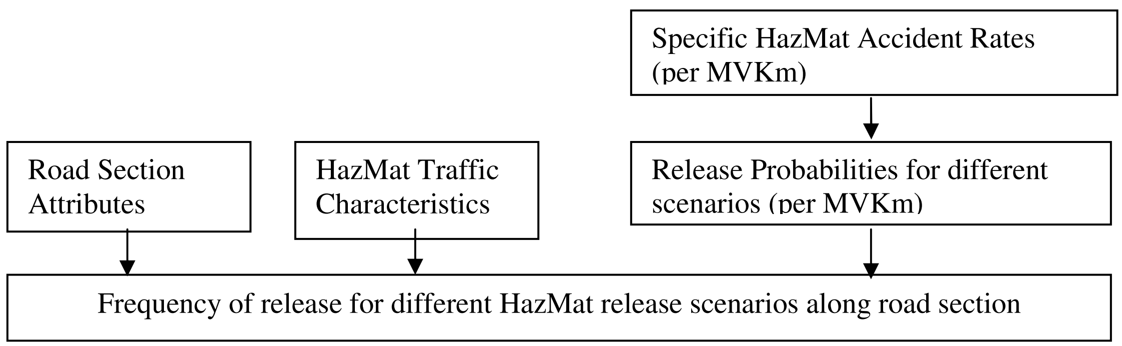


Figure 4-1: Estimating releases frequencies for different release scenarios

The annual frequency of occurrence of scenario *kr* on link *l*, $Freq_l^{kr}$, can then be estimated by combining release rates and HazMat traffic exposure as follows:

$$Frq_l^{kr} = AR * P\left(RL^{kr} \mid A\right) * AADT_l^k * L_l * 365 * 10^{-6} \qquad \textbf{(4-2)}$$

Here:

AR	is the truck accident rate, measured in accidents per Million Vehicle-Kilometers (MVKm) traveled and assumed to be the same for all types of HazMat.

$P(RL^{kr} \mid A)$ is the probability of a type *r* release for a given HazMat type *k* taking place given a HazMat accident.

$AADT_l^k$ is the average annual daily traffic of HazMat type *k* on link *l*.

L_l is the length of link *l* in km.

In the following sections, we introduce estimates for the input parameters required for frequency analysis.

4.2 HazMat Truck Accident Rates (AR_l)

Truck accident rates depend on a number of features, such as road type and conditions, posted speed, and environmental conditions. However, estimates of truck accident rates are normally based on characteristics of broad classification or road type (e.g. urban versus rural) of which useful data is available. Accident rates can be expressed differently according to various measures for exposure, with examples ranging from accidents per shipment, to accidents per ton, …per route, …per month, …per year, etc. In this module, accident rates are reported in terms of the number of accident involvements per Million Vehicle-Kilometers traveled (MVKm).

A review of various studies revealed a difference in estimating truck accident rates. In an early work, Saccomanno et al (1989) used statistical models calibrated on Ontario highway data to estimate truck accident rates (Table 4-1). Conversely, Russell and Harwood (1993) provided a set of truck accident estimates based on data from three US states, namely, California, Illinois, and Michigan. The results of their analysis are provided in Table 4-2 and show a great difference in truck accident rate estimates.

Table 4-1: Truck accident rates by highway type for Ontario /MVK

Highway Type	Accident rate
Urban	1.00
Suburban	0.76
Rural	0.47

Table 4-2: Truck accident rates by highway type for California, Illinois and Michigan combined

Area	Highway class	Truck accident rate (/MVMile)
Rural	Tow-lane	2.19
Rural	Multilane, undivided	4.49
Rural	Multilane, divided	2.15
Rural	Freeway (limited access)	0.64
Urban	Tow-lane	8.66
Urban	Multilane, undivided	13.92
Urban	Multilane, divided	12.47
Urban	One-way street	9.70
Urban	Freeway (limited access)	2.18

Saccomanno et al. (1998) proved that estimates for truck accident rates vary for different countries. They obtained truck accident rates by highway class for different North American and European jurisdictions. Three classes of surface routes were considered: urban, rural, and non-primary highways (national non-freeways). Table 4-3 provides a breakdown of truck surface highway accident rates for Ontario as reported by Saccomanno et al. (1998). These rates were obtained using reportable road accidents from Ontario Accident Data System (ADS) for the period 1988 to 1992. Saccomanno et al. (1998) also reported different values for truck accidents in California, The Netherlands, France and Norway as shown in Table 4-4.

Table 4-3: Truck accident rates by highway type for Ontario (per MVKm)

Highway Type	Ontario Global Rate
Urban	1.023
Rural	0.549
Arterials	1.003
Overall	0.924

Table 4-4: Truck accident rates by highway type for different countries (per MVKm)

Highway Type	California Global Rate	Netherlands Global Rate	France Global Rate	Norway Global ate
Urban	0.99	0.492	0.973	1.431
Rural	0.33	0.164	0.324	0.477
Arterials	1.548	0.768	1.522	2.238

A comparison of Ontario truck accident rates estimates in Table 4-3 and Table 4-1 for urban and rural highways shows little difference, mainly because the figures were based on the same accident data system. However truck accident rate estimates differ significantly for different countries (Table 4-2, Table 4-3, and Table 4-4). The Ontario truck accident rates estimates by Sacommanno et al. (1998) are used in the TDQRA analysis (Table 4-3).

4.3 *HazMat Release Probabilities Given an Accident ($P_l\left(RL^{kr} \mid A\right)$)*

The accuracy of HazMat risk assessment would be greatly improved by better estimates of HazMat release rates. However, HazMat release data are scarce, giving rise to great uncertainty. Thus, after investigating different release probability estimates, we found considerable variance in release probability estimates, depending on assumptions, methodology, and data used.

In Canada, Saccomanno et al. (1989) reported road transport release probabilities given an accident for different HazMat types (Table 4-5), and probabilities for different release types (high, medium, and low) given a release for both instantaneous and continuous releases[5] (Table 4-6).

Table 4-5: Release probabilities given an accident for HazMat road transport (Saccomanno et al. 1989)

HazMat type	Total # of release/yr	Probability of release given accident
Chlorine	0.5	0.016
LPG	0.8	0.037
Gasoline	3.5	0.12

Table 4-6: Conditional probabilities (%) of different release volumes given a release (Saccomanno et al. 1989)

	Release probability (%)						Released quantity					
	Instant.			Continuous			Instant. (% of tanker capacity*)			Continuous (kg/sec)		
HazMat type	High	Med	Low	High	Med	Low	High	Med	Low	High	Med	Low
Chlorine	18	22	31	12	8	9	95	80	60	14.5	3.9	0.10
LPG	10	20	20	10.5	5.2	1.3	95	80	60	4	16	30
Gasoline	40	-	60	-	-	-	95	80	60	-	-	-

*Tanker capacity: chlorine 20 ton, LPG 26 ton, Gasoline 20 ton.

[5] Instantaneous release is the sudden loss of HazMat in a short period of time, while continues release is the loss of HazMat in a constant or near constant rate over a long period of time (US Environmental Protection Agency & National Oceanic and Atmospheric Administration 1999).

In the UK, the Health and Safety Executive (1991) gave estimates for release frequencies regardless of HazMat type, as shown in Table 4-7.

Table 4-7: UK Health and Safety Evacuative estimates for release frequencies for all HazMat types

Release type	Release frequency per truck km
Large*	0.7*10E-8
Medium	4.8*10E-8
small	2.9*10E-8

*Large spill is over 1500 kg, medium spill is between 150 kg and 1500 kg, and small is less than 150 kg.

Finally, a more recent study by Button (1999) reported release rate estimates by HazMat type (toxic liquefied gases, flammable liquefied gases, flammable liquids, and toxic liquids), load type (large load and small load), and accident outcome (collision and overturn, only collision, only overturn, and no collision with no overturn). These estimates (Table 4-8) were used in this research since they are based mainly on DGAIS data and are consistent with using the discharge rates estimated from DGAIS data in Section 3.3.5. An event tree of different releases for a certain type of HazMat is shown in Figure 3-1.

Table 4-8: Release probability estimates (%) for different Hazmat types, load type, and accident outcome (Button 1999)

scenario	overturn	collision	large load	HazMat type (k)**	Release probability* by release type (r)				no release	Total
					Large spill	small spill	large leak	small leak		
1	y	y	y	1	22.09	2.98	1.75	1.45	71.73	100
2	y	y	y	2	24.04	3.24	1.91	1.57	69.25	100
3	y	y	y	3	37.32	12.85	2.96	2.44	52.25	100
4	y	y	y	4	14.03	1.9	1.11	0.92	82.05	100
5	y	y	n	1	9.58	12.3	1.04	5.35	71.73	100
6	y	y	n	2	10.45	13.35	1.14	5.84	69.25	100
7	y	y	n	3	16.21	20.73	1.76	9.05	52.25	100
8	y	y	n	4	6.1	7.79	0.66	3.41	82.05	100
9	y	n	y	1	22.09	2.99	1.75	1.45	71.73	100
10	y	n	y	2	24.04	3.23	1.91	1.57	69.24	100
11	y	n	y	3	37.32	5.04	2.96	2.44	52.25	100
12	y	n	y	4	14.03	1.89	1.11	0.92	82.05	100
13	y	n	n	1	9.58	12.29	1.04	5.36	71.73	100
14	y	n	n	2	10.45	13.35	1.13	5.83	69.24	100
15	y	n	n	3	16.22	20.55	1.76	9.05	52.25	100
16	y	n	n	4	6.09	7.79	0.66	3.4	82.05	100
17	n	y	y	1	0.3	0.04	0.02	0.02	99.62	100
18	n	y	y	2	0.53	0.07	0.05	0.04	99.32	100
19	n	y	y	3	0.31	0.05	0.02	0.02	99.61	100
20	n	y	y	4	0.19	0.03	0.01	0.01	99.75	100
21	n	y	n	1	0.13	0.17	0.01	0.07	99.62	100
22	n	y	n	2	0.23	0.3	0.02	0.13	99.32	100
23	n	y	n	3	0.13	0.17	0.01	0.07	99.61	100
24	n	y	n	4	0.09	0.11	0.01	0.05	99.75	100
25	n	n	y	1	0.3	0.04	0.02	0.02	99.62	100
26	n	n	y	2	0.53	0.08	0.04	0.03	99.32	100
27	n	n	y	3	0.31	0.04	0.02	0.02	99.61	100
28	n	n	y	4	0.2	0.03	0.02	0.01	99.72	100
29	n	n	n	1	0.13	0.17	0.01	0.08	99.62	100
30	n	n	n	2	0.23	0.3	0.02	0.13	99.32	100
31	n	n	n	3	0.14	0.17	0.01	0.08	99.61	100
32	n	n	n	4	0.09	0.1	0.01	0.05	99.75	100

*Original estimates were aggregated to give combined fire and non-fire release probabilities

**HazMat type: 1 = toxic liquefied gas (Ammonia)
2 = flammable liquefied gas (Propane)
3 = flammable liquid (Gasoline)
4 = toxic liquid

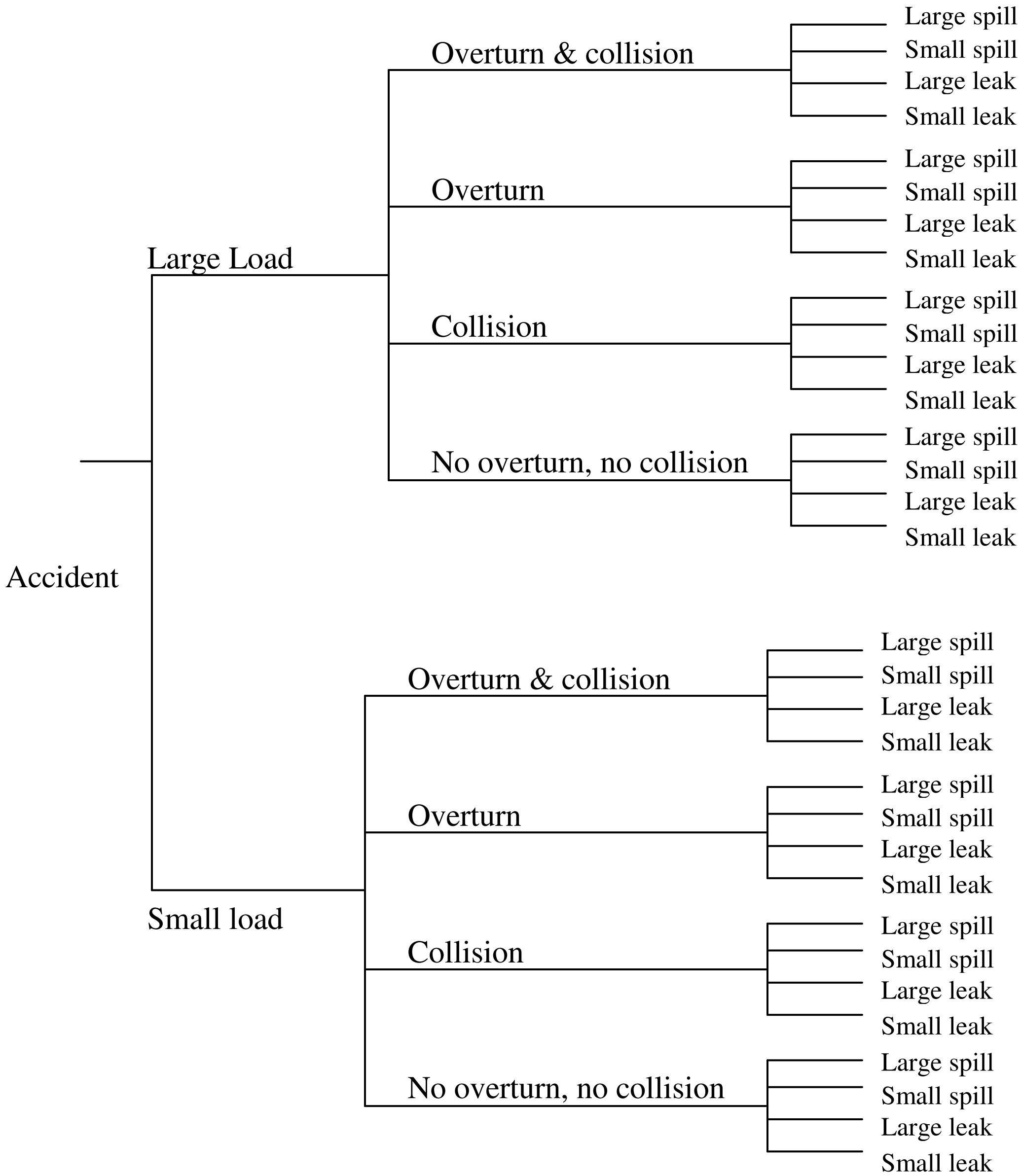


Figure 4-2: Event tree of HazMat releases of a certain type of HazMat

The probability of release type *r* for HazMat type *k* given an accident, $P\left(RL^{kr} \mid A\right)$, is calculated as follows:

$$P\left(RL^{kr} \mid A\right) = \sum_{A_o} \sum_{L_s} P\left(RL^{kr} \mid A_o L_s\right) * P_l\left(A_o \mid A\right) * P_l\left(L_s\right) \qquad \textbf{(4-3)}$$

Where:

A_o	accident outcome (overturn & collision, overturn, collision, no overturn no collision)
L_s	load size (large, small)
$P\left(RL^{kr} \mid A_o L_s\right)$	probability of release type *r* for HazMat type *k* given accident outcome A_o and load size L_s
$P\left(A_o \mid A\right)$	probability of accident outcome " A_o " given an accident
$P(L_s)$	probability of load size " L_s "

The following equation is an example of how to calculate an Ammonia large spill release probability:

P (Ammonia large spill) =
P (Ammonia large spill | overturn & collision, large load) * P (overturn & collision) * P (large load)
+P (Ammonia large spill | overturn, large load) * P (overturn) * P (large load)
+P (Ammonia large spill | collision, large load) * P (collision) * P (large load)
+P (Ammonia large spill | no overturn & no collision, large load) * P (no overturn & no collision) * P (large load)
+ P (Ammonia large spill | overturn & collision, small load)* P (overturn & collision) * P (small load)
+P (Ammonia large spill | overturn, small load) * P (overturn) * P (small load)
+P (Ammonia large spill | collision, small load) * P (collision) * P (small load)
+P (Ammonia large spill | no overturn & no collision, small load) * P (no over turn & no collision) * P (small load)

Saccomanno et al. (1998) provided Ontario estimates for the probability of different accident outcomes, A_o, and load types, L_s. Accordingly, they estimated that 48% of the shipments in Ontario carry large loads, while 52% carry small loads. Table

4-9 shows the accident outcomes probability estimates for trucks on Ontario highways, with different HazMat release probabilities estimated by applying the Ontario load type and accident outcome probabilities to Button's release estimates for different scenarios. Table 4-10 lists the resulting release frequencies.

Table 4-9: Accident outcome probabilities (A_o) for accidents on 400 level highways.

	Collision & Overturn	Collision	Overturn	No Collision/Overturn	Total
Percentage	0.016	0.843	0.027	0.115	1

Table 4-10: Release probabilities (%) by HazMat type

HazMat type	large spill	small spill	large leak	small leak	total
toxic liquefied gas	0.87	0.44	0.08	0.19	1.58
flammable liquefied gas	1.09	0.55	0.10	0.24	1.98
flammable liquid	1.34	0.73	0.12	0.30	2.49
toxic liquid	0.56	0.28	0.05	0.12	1.02

4.4 HazMat Traffic Movements

HazMat release frequencies are obtained by applying truck accident rates and HazMat release rates to the HazMat traffic volumes on links. However, obtaining reliable information on HazMat routes and volumes is not an easy task since such information is not readily available for planners. As a result, different approaches have been used to estimate HazMat traffic volumes with the US Environmental Protection Agency (1990) suggested the following suggestions:

- Using truck traffic surveys. The “1999 National Roadside Study” (Canadian Council of Motor Transport Administrators Coordinates 2002), and “Canadian Vehicle Survey” are two examples of such surveys. An example of using data from these surveys to estimate HazMat movements for risk assessment may be found in Brown et al. (2001).
- Information could be obtained from the police and fire department personnel regarding what hazardous materials pass through a community, the routes most frequently used, and the frequency of transport.
- Truck weighing stations in or around the jurisdiction may be a source of information on the number of placarded loads moving through the area.
- Directly contacting a carrier’s or shipper's office regarding movements and load contents.
- Reviewing of permit records. Companies that handle HazMat usually require a variety of permits which might provide useful information on HazMat types and movements within communities.

In this research, the percentage of HazMat volumes for total truck traffic in Canada was estimated using data provided by the 1995 National Roadside Study (Canadian Council of Motor Transport Administrators coordinates 1997). The study collected data at 148 survey sites spread across the 25,600 kilometers of the Survey Highway System. Two types of information were collected at each site: a 7 day count of trucks passing the site, classified by day, time and truck type, and interviews of a random sample of the passing trucks (80 questions in interview). In total, the 148 sites counted 1,040,163 trucks and interviewed 36,242 trucks (3.5%).

For this research, the percentage of HazMat movements in total truck traffic for different HazMat classes was estimated based on the "1995 Road Side Survey" data[6]. Table 4-11 shows that HazMat accounts for 9.85% of all truck movements by ton on the survey roads. Although these estimates are based on truck movements on survey roads, we can generally assume they are applicable for all truck traffic in Canada. The percentages of different HazMat types in the total HazMat traffic were obtained from Transport Canada (2002) as shown in Table 4-12.

Table 4-11: Estimated percentage of different HazMat types transported on Canadian roads (by ton)

Class (as defined in DGTR*)	Percent
1	0.08
2	1.20
3	5.09
4	0.30
5	0.75
6	0.13
7	0.09
8	0.97
9	0.12
Cargo includes HazMat, but unable to determine class	1.12
Total HazMat	9.85
Total Non-HazMat	90.15
Total	100.00

*See definition of "dangerous goods" in "Glossary"

[6] using "WesVarPC2.02" software developed by Westat.

Table 4-12: Percentage of top HazMat transported by road (by tonnage), reported by Transport Canada.

Classification	Shipping name	percent	Total percent
Flammable liquids	Gasoline	22.97	64.61
	Fuel Oil	17.53	
	Tars	7.82	
	Petroleum Crude Oil	6.69	
	Ethanol	2.92	
	Aviation fuel	1.58	
	Flammable Liquids preparations	1.51	
	Flammable Liquids n.o.s.	1.36	
	Paint	0.92	
	Resin Solutions	0.88	
	Medicines, n.o.s.	0.43	
Corrosive liquids	Corrosive Liquids n.o.s.	10.44	14.62
	Caustic Soda	2.18	
	Sulphuric Acid	1.60	
	Hydrochloric Acid	0.40	
Flammable liquefied gases	Propane	1.85	3.58
	Petroleum Gases	1.15	
	Butane	0.58	
Toxic liquefied gases	Ammonia	0.98	0.98
		Total	83.79
Other HazMat material (do not fall under the previous 4 classification of HazMat and/or transported in small amounts)			16.21

4.5 Summary

In this chapter we presented a method for estimating release frequencies, in terms of expected number of releases, for different release scenarios and HazMat type. Only accident-induced releases were considered since they dominate the risk of HazMat transport. Frequencies were first estimated on links and then aggregated to adjacent nodes. Methods for estimating accident rates, release probabilities, and HazMat movements were discussed. Frequency estimation is the first component of quantitative risk analysis; the second component, consequence estimation, will be discussed in Chapter 5.

CHAPTER 5: ANALYSIS OF HAZMAT RELEASE CONSEQUENCES

This chapter discusses how to estimate the magnitude of damage associated with a given release of HazMat. Consequence damage, hence consequences analysis, differs for different types of HazMat. The analysis starts with defining outcomes of different HazMat releases: a toxic cloud is the only outcome for the release of toxic liquefied gas; while, in case of flammable liquids ignition for both immediate and delayed ignitions, the final outcome is a pool fire with potential radiant heat effects[7]. Ignition of released flammable liquefied gases will have several possible outcomes (US Environmental Protection Agency 1999), namely,

- Vapor cloud fires (flash fires): flammable vapor clouds when ignited could flash back creating a severe heat radiation hazard to anyone in the area of the cloud. Hazard area includes the whole region within the lower flammability limit (LFL) of released HazMat.

- Vapor cloud explosions (VCE): For a vapor cloud explosion to occur, rapid release of a large quantity, turbulent conditions, and other factors are generally necessary. Vapor cloud explosions generally are considered unlikely events.

[7] ARCHIE gives the equivalent radius for the fatality zone.

- BLEVE: A boiling liquid, expanding vapor explosion may occur if a tanker truck containing flammable materials ruptures explosively as a result of exposure to fire. Heat radiation from the fireball is the primary hazard, while fragments and overpressure from the explosion can also pose hazard. BLEVEs are generally considered unlikely events.

- A jet fire resulting from the puncture or rupture of a tank containing a compressed or liquefied gas under pressure. The gas discharging from the hole can form a jet that "blows" into the air in the direction of the hole, with the jet possibly igniting. Jet fires could contribute to BLEVEs and fireballs if they impinge on tanks of flammable substances.

The UK Health and Safety Executive (1991) assumes 90% of flammable vapor clouds that ignite will result in flash fire with a 100% lethality within LFL and 0% lethality outside the LFL. In the case of the other 10%, VCE is assumed to occur.

Since the occurrence of VCE will hardly result in more fatalities than a flash fire, and due to BLEVE and jet fire considered as unlikely events, we chose to model all LPG ignition outcomes as flash fire. However, in future enhancement of the system, detailed consideration of other incident outcomes may be added.

Figure 5-1 illustrates possible incident outcomes in the case of a HazMat release. Table 5-1 lists incident outcomes considered in our TDQRA module for different HazMat types.

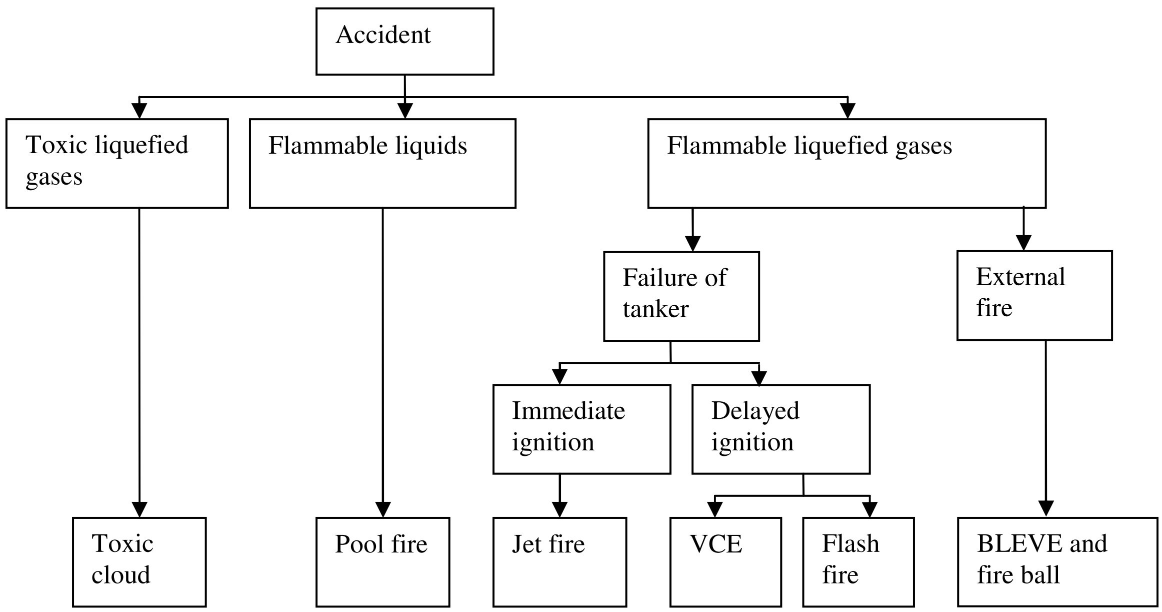


Figure 5-1: Possible outcomes of HazMat releases

Table 5-1: Modeled release outcomes for the TDQRA module

HazMat type	Release outcome
Liquefied toxic gas	Toxic cloud
Liquefied flammable gas	Vapor cloud fires (Flash fire)
Flammable liquids	Pool fire

5.1 Consequences of Release of Toxic Liquefied Gas (Ammonia)

This section discusses consequences from a toxic liquefied gas (Ammonia) release. The following steps represent the progress in case of an Ammonia release:

1) Release occurs. The amount of release and the discharge rate determine the classification of the release as a spill or leak, large or small.
2) The released substance starts to evaporate and a vapor cloud starts to form. The rate of evaporation depends on many factors including atmospheric temperature, and wind conditions.
3) Different levels of concentrations of the gas develop, starting with high concentration from the release site and decreasing outwards depending on the meteorological conditions. These levels of concentration are usually referred to as isopleths, or hazardous envelops.
4) Population is exposed to different concentration levels of HazMat for a period of time resulting in fatalities and/or injuries.

5.1.1 Release and Heavy Gas Dispersion

Consider a release of pressurized liquefied gas, such as Ammonia or Propane, at a given location (node *j*) as shown in Figure 5-2. The liquefied gas will normally be released in liquid form but will start to evaporate into the surrounding atmosphere, forming a hazardous cloud. With time, and depending on atmospheric conditions, the cloud is diluted further by air entrainment and disperses as a plume. Next, the gas dispersion results in different levels of concentration starting with higher concentration near the point of release and decreasing outwards. Boundaries of different levels of concentration are usually referred to as hazard envelopes, or isopleths. Lastly, the size of different hazard envelopes depends on many factors, e.g. discharge rate, meteorological conditions, and release duration.

In this research, the continuous space of the hazard area is transformed into a discrete one by modeling it as a mesh grid associated with a Cartesian coordinate system as shown in Figure 5-2. Careful choice of grid size is of great importance since it will affect risk estimates. The tradeoff between accuracy and computational efficiency should also be considered since finer grid cells will result in better risk estimates, but will also increase computational effort.

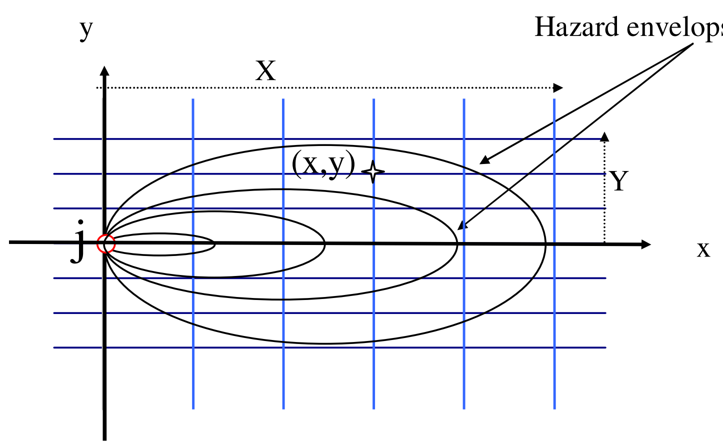


Figure 5-2: Illustration of hazard cloud and dispersion process

At point (*x, y*) within the hazard area and after release duration, t_{ij}, the concentration level of release type *r* for HazMat type *k*, $C_{t_{ij}}^{kr}(x, y)$, could be obtained using a gas dispersion model. A wide range of atmospheric dispersion models is available. Mazzola et al. (1995) provided an overview of available gas dispersion models with a compilation and description of 94 computer-generated atmospheric dispersion models. Many of these models were initially investigated.

After a careful comparison, the two widely used models ALOHA (Areal Locations of Hazardous Atmospheres) and ARCHIE (Automated Resource for Chemical Hazard Evaluation) were chosen for closer investigation. Eventually, the conclusion was made to use ALOHA since it gives both concentration level and dose at any point (x,y) associated with a release duration, t_{ij}. Appendix C gives a brief discussion of ALOHA.

ALOHA requires different parameters for modeling gas dispersion such as HazMat type, discharge rate, release duration, immediate danger to health and life (IDHL) level for toxic materials (or Lower Flammability Level for flammable materials), as well as weather and terrain conditions. ALOHA uses the information about the type of HazMat released, rate of release, and weather conditions to provide the concentration level (in ppm) at any point (x,y) as well as a gas dispersal "footprint". Accordingly, ALOHA's footprint for a certain concentration level corresponds to hazard envelop for that concentration level.

ALOHA was run separately for different release scenarios (*kr*) and weather conditions, with the results then incorporated in the TDQRA module. The following example illustrates an ALOHA run for a large spill of Ammonia at a rate of 336 kg/min for up to 30 minutes. The resulting footprint is shown in Figure 5-3:

SITE DATA INFORMATION:

Location: TORONTO, CANADA

Building Air Exchanges Per Hour: 0.74 (sheltered single storied)

Time: April 15, 2003 1513 hours DST (user specified)

CHEMICAL INFORMATION:

Chemical Name: AMMONIA Molecular Weight: 17.03 kg/kmol

TLV-TWA: 25 ppm IDLH: 300 ppm

Footprint Level of Concern: 1120 ppm

Boiling Point: -33.43° C

Vapor Pressure at Ambient Temperature: greater than 1 atm

Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC INFORMATION: (MANUAL INPUT OF DATA)

Wind: 4.87 meters/sec from w at 3 meters

No Inversion Height

Stability Class: D Air Temperature: 21° C

Relative Humidity: 50% Ground Roughness: 50 centimeters

Cloud Cover: 5 tenths

SOURCE STRENGTH INFORMATION:

Direct Source: 335.9647 kilograms/min

Source Height: 0

Release Duration: 30 minutes

Discharge rate: 336 kilograms/min

Total Amount Released: 10,079 kilograms

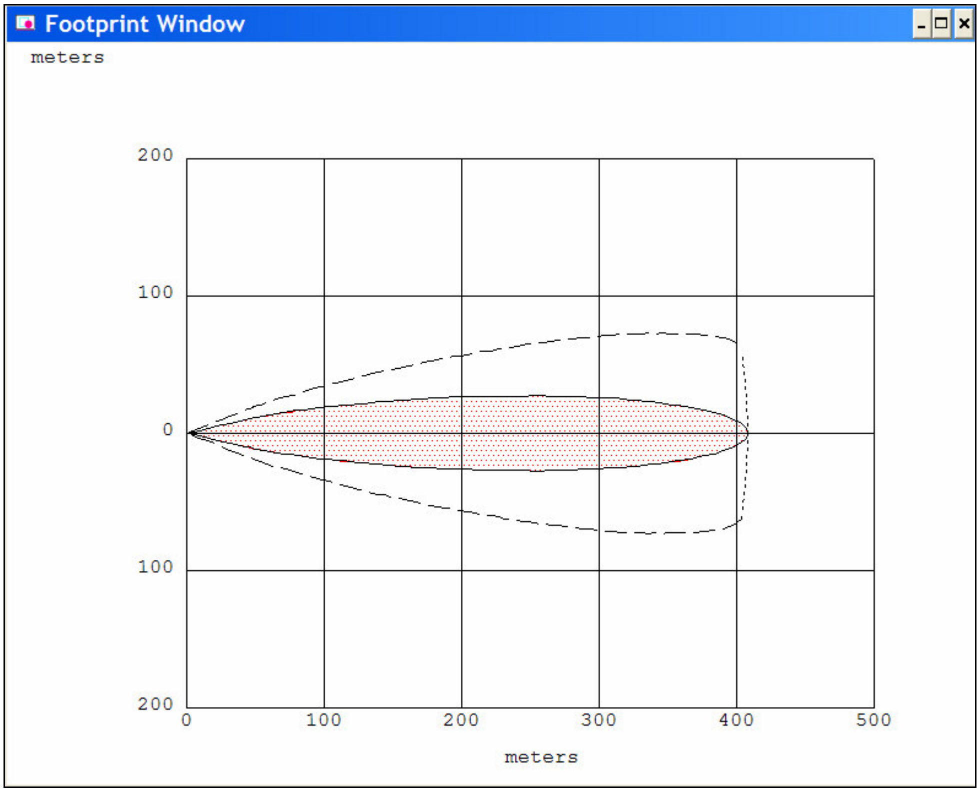


Figure 5-3: ALOHA footprint for a release of Ammonia at a rate of 336 kg/min for a duration of 30 minutes

5.1.2 Vulnerability and Lethality for Toxic Gases

Concentration levels obtained from gas dispersion models are used to calculate Lethality (or vulnerability) levels at a given point (*x*,*y*) within the hazard area. Vulnerability is defined as the probability that an individual will experience a certain level of an undesirable consequence as a result of a release. Lethality is the vulnerability when the undesirable consequence is death. Lethality level, $LL_{t_{ij}}^{kr}(x, y)$, is defined as the probability of a person residing at point (*x*,*y*) being killed after exposure to a release type *r* of HazMat type *k* for a time t_{ji}. In case of the release of toxic liquefied gases such as Ammonia, $LL_{t_{ij}}^{kr}(x,y)$ is a function of the concentration level, $C_{t_{ij}}^{kr}(x,y)$.

Referring to Figure 5-2, we define X as downwind distance from release point to the 1% lethality level and Y as maximum crosswind distance to 1% lethality level. ALOHA is used to calculate $C_{t_{ij}}^{kr}(x,y)$ for x = 0 to X and y = 0 to Y. Once $C_{t_{ij}}^{kr}(x,y)$ at point (*x,y*) has been calculated, its combination with the exposure time, t_{ij}, gives the "toxic load" or "absorbed dose", $D_{t_{ij}}^{kr}(x,y)$, usually referred to as "dose". The following equation gives $D_{t_{ij}}^{kr}(x,y)$ after release time t_{ij} when the concentration level $C_{t_{ij}}^{kr}(x,y)$ is constant over time:

$$D_{t_{ij}}^{kr}(x,y) = [C_{t_{ij}}^{kr}(x,y)]^m * t_{ij} \tag{5-1}$$

Where *m* is a HazMat specific parameter

Due to the dynamics of gas dispersion, the concentration level at a given location is likely to vary over time. For a variable concentration over time, the dose could be calculated by integrating $C_{t_{ij}}^{kr}(x,y)$ over time t from t =0 to t= t_{ji} according to the following equation:

$$D_{t_{ij}}^{kr}(x,y) = \int_0^{t_{ij}} [C_{t_{ij}}^{kr}(x,y)]^m \, dt \tag{5-2}$$

Figure 5-4 shows the variation in dose with the release duration along the centerline downwind of the release site for a large spill of Ammonia for a duration of 30 minutes

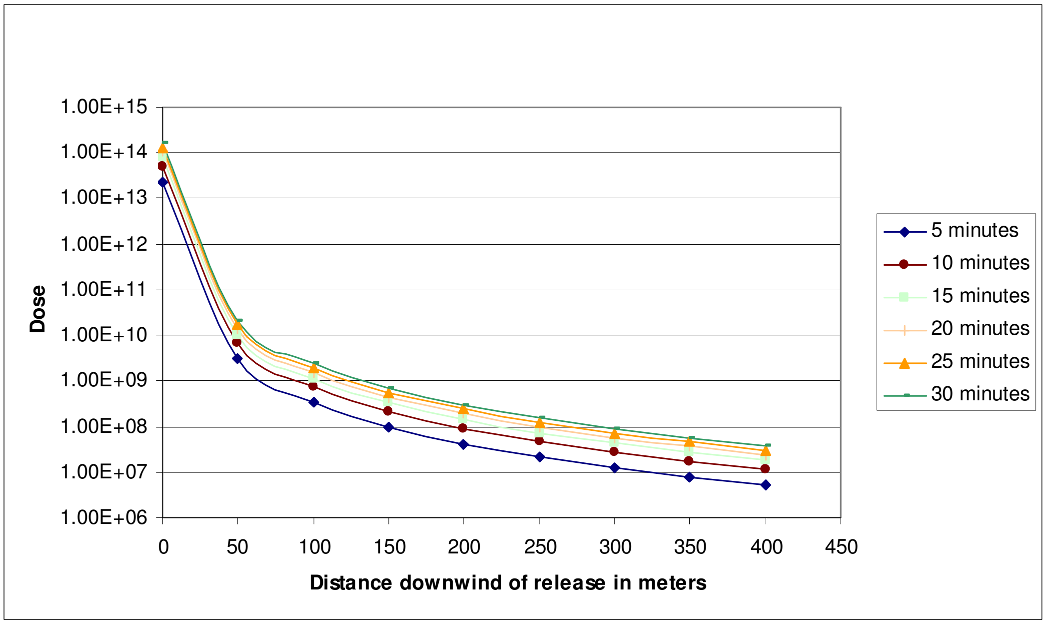


Figure 5-4: Variation in dose with time along centerline downwind of release site for a large a Ammonia spill

The absorbed dose could be linked to the damage on an average individual using a "probit" (probability unit) function (TNO 1992). The probit value at *(x,y)* for an exposure time t_{ij}, $\Pr_{t_{ij}}^{kr}(x, y)$, can be generally defined as:

$$\begin{aligned}\Pr_{t_{ij}}^{kr}(x, y) &= a + b * \ln\left(D_{t_{ij}}^{kr}\right) \\ &= a + b * \ln\left([C_{t_{ij}}^{kr}(x, y)]^m * t_{ij}\right)\end{aligned} \qquad \textbf{(5-3)}$$

The terms a, b and m are model parameters that can be calibrated through empirical analyses. For Ammonia, Technica Ltd (1985) suggested values for $a = -9.82$, $b = 0.71$, and $m = 2$.

The probit has a normal distribution with a mean value of 5 and a standard deviation of 1. Lethality level, $LL_{t_{ij}}^{kr}(x, y)$, is related to the probit as follows:

$$LL_{t_{ij}}^{kr}(x, y) = \int_{-\infty}^{Z_o} \frac{1}{\sqrt{2\pi}} e^{\frac{z^2}{2}} dz \tag{5-4}$$

where $Z_o = \dfrac{\Pr_{t_{ij}}^{kr}(x, y) - 5.0}{1.0}$

Probit values corresponding to 10%, 50% and 90% lethality levels are 3.72, 5.0, and 6.28, respectively.

Figure 5-5 shows the variation in lethality levels with time along the centerline downwind of the release site for a large Ammonia spill. The lethality level at the source is shown as 100% regardless of the release duration. Moving away from the release site, release duration becomes more significant. Effect of the release duration is greatest at about 100 meters downwind of the release site. As distance from the release point further increases, the effect of the release time decreases.

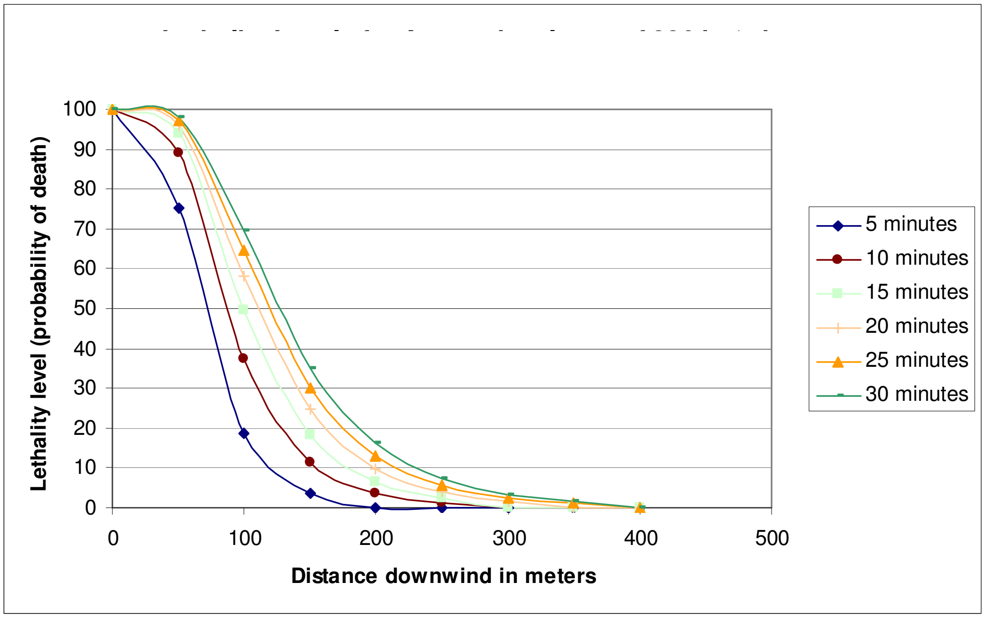


Figure 5-5: Variation in lethality level distribution with time along centerline downwind of release site for a large Ammonia spill

5.1.3 Consequence Calculations for Toxic Clouds

Combining the level of lethality at each point (x,y) with its population density produces the number of consequence at that point, $Csq_{t_{ij}}^{kr}(x, y)$, according to the following equation:

$$Csq_{t_{ij}}^{kr}(x, y) = LL_{t_{ij}}^{kr}(x, y) * pop(x, y) * (\Delta x, \Delta y) \quad \textbf{(5-5)}$$

Where:

$pop(x, y)$ population density at point (x,y)

Δx grid cell length

Δy grid cell width

The consequences at node *j* when emergency response is initiated from location *i*, Csq_{ij}^{kr} , is obtained by summing consequences of all grid cells within the hazard area.

$$Csq_{ij}^{kr} = \sum_{y=0}^{Y} \sum_{x=0}^{X} Csq_{t_{ij}}^{kr}(x, y) \qquad \textbf{(5-6)}$$

Where:

X is maximum downwind distance from release point *j* to the 1% lethality level

Y is maximum crosswind distance to 1% lethality level.

Population density is assumed to be homogeneous for the whole hazard area around the release site, and thus a single population density value is used for each individual node. Initially we considered having different population densities for different points within the hazard area around release node *j*. However, given that release frequencies on links were aggregated to the nearest node, this approach might not yield better risk estimates. Many nodes represent population centers where population density is higher than that on transportation links. Hence, considering detailed population density at nodes might overestimate HazMat risk at these locations. Using an average population density is consistent with the level of aggregation used for estimating release frequencies at nodes.

Using ALOHA, the Ammonia release was modeled as a toxic dense gas release. A lethality level threshold of 1% was used to determine the hazard area (i.e. X and Y values). Intervals of one minute were used to calculate lethality levels at different response times. Figure 5-6 and Figure 5-7 show the expected consequences for different Ammonia spills, small and large respectively, using unit population density (1 inhabitant/km^2).

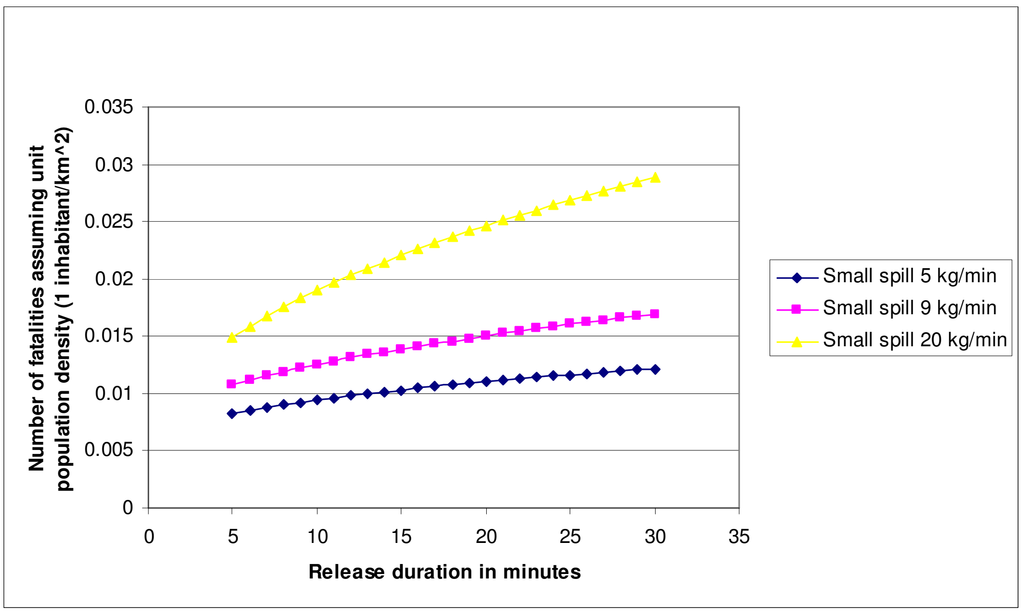


Figure 5-6: Expected consequences for different rates of Ammonia small spill

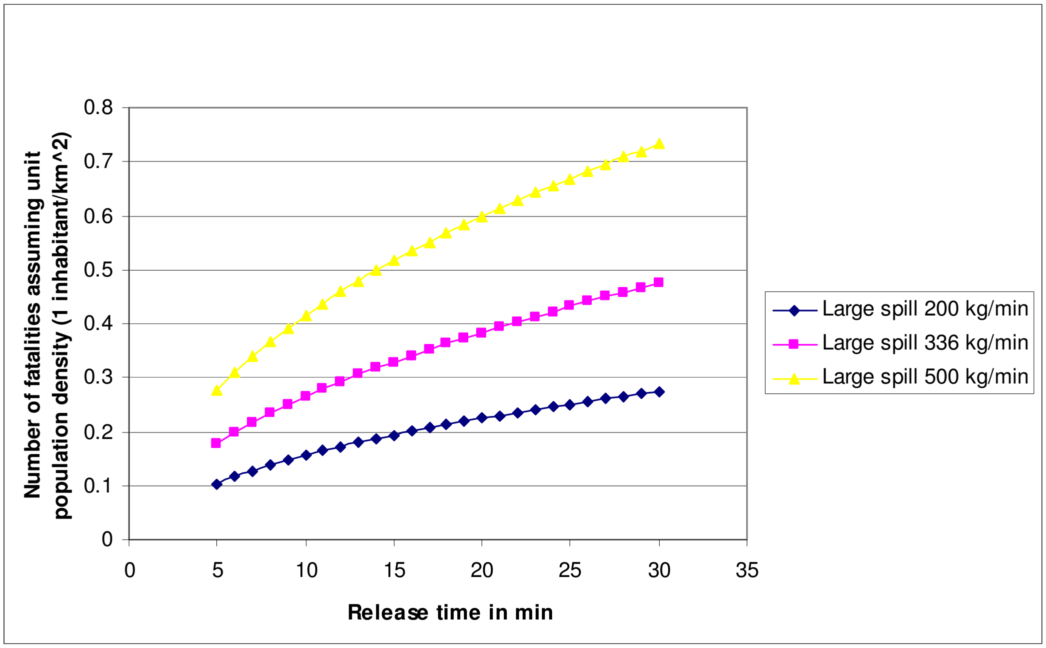


Figure 5-7: Expected consequences for different rates of Ammonia large spill

5.2 Consequences of Release of Flammable Liquefied Pressured Gases (LPG)

The release of flammable liquefied pressurized gases (LPG, e.g. Propane) results in a rapid evaporation of the released liquid and the formation of vapor cloud. In this research, vapor cloud fire (flash fire) is the outcome considered for modeling the ignition of flammable vapor cloud following dispersion. Ignition of the cloud depends on the concentration of the flammable gas: if the vapor cloud is too rich (above Upper Flammability Level, UFL) there may not be enough oxygen for it to ignite; if the cloud is too diluted (below Lower Flammability Level, LFL) there may not be enough flammable substance for the cloud to ignite. Furthermore, if a cloud within flammability levels reaches an ignition source, it will ignite and flash back to the release source.

Gas dispersion modeling of flammable LPG is the same as for toxic liquefied gases (Section 5.1.1). As in Ammonia consequence analysis, the continuous space of the hazard area is transformed into a discrete mesh grid. ALOHA is used to calculate concentration levels at different grid cells. Cells with concentration levels within the LFL are considered as hazard area ($HA_{t_{ij}}^{kr}$) as shown in Figure 5-8. Unlike toxic gases, we are only interested in concentration levels equal to the lower flammability limit (LFL)[8] since the assumption is made that once ignition occurs, the whole hazard area within the LFL will ignite regardless of concentration levels.

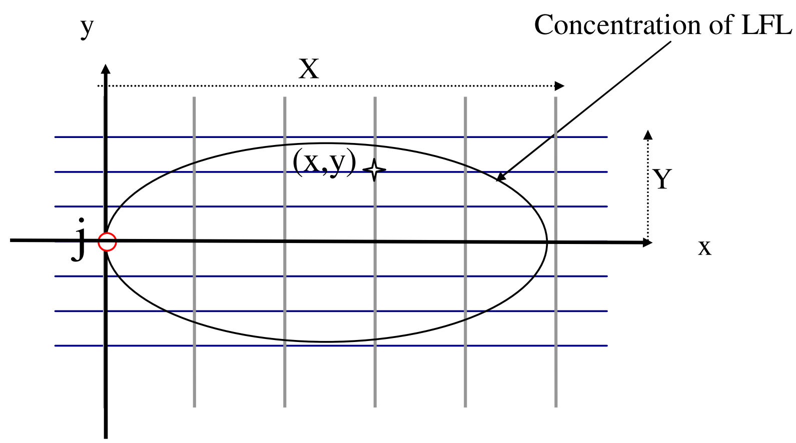


Figure 5-8: Hazard area within the LFL of flammable cloud

5.2.1 Ignition Probabilities, an Overview

Ignition probability estimates for flammable clouds have great uncertainty associated with them. Many QRA models rely on either experts' guesses or sparse

[8] Propane has an UFL of 9.5% by volume (or 95,000 ppm[8]) and a LFL of 2.1% (or 21,000 ppm).

historical data for ignition probability estimates. Cox et al (1990) and Center for Chemical Process Safety (1995) give a review of the subject. Approaches used to estimate ignition probabilities include,

- **Estimates based on cloud area:**

Simmons (1974) did one of the earliest studies on ignition probability. His model estimates the cumulative probability of ignition as a function of cloud area for LPG and LNG (Liquefied Natural Gas) releases, based on 59 incidents. Table 5-2 gives the model cumulative ignition probabilities for different cloud areas.

Table 5-2: Cumulative ignition probabilities based on cloud area (Simmons 1974)

Area (m^2)	cumulative ignition probability, E_A
30	0.5223
300	0.7364
3,000	0.8866
30,000	0.9629
300,000	0.9909
3,000,000	0.9983

- **Estimates based on location of cloud at ignition:**

U.K. Health and Safety Executive (1991) estimated values of the conditional delayed ignition probability given that prior ignition has not occurred. The estimated values are shown in Table 5-3. These estimates were based on judgment.

Table 5-3: U.K. Health and Safety Executive estimates of delayed ignition probabilities

Type of ignition	Conditional probability
Edge of the cloud is at edge of population area when ignition occurs	0.7
Cloud is right over population area at time of ignition	0.2
No ignition	0.1

- **Estimates based on discharge rate:**

Cox et al. (1990) suggested a correlation for the probability of ignition based on discharge rate. The probability of ignition (immediate and delayed) was assumed as a function of a power of the discharge rate as follows: $P = a\ m^b$, where P is the ignition probability, m is the discharge rate (kg/s), and a and b are model parameters.

- **Estimates based on detailed consideration of ignition sources:**

Rew et al. (2000) developed an ignition probability model that is based on the distribution of likely ignition sources at the release site and considers (among other factors) the release duration. The model requires detailed data related to types and densities of different ignition sources within the release site. This model was developed for use in the UK; however, such data was unfortunately not available for use in Canada.

- **Estimates based on release size**

Brown et al. (2001) found that the ignition probability strongly depends on release amounts, as shown in Table 5-4. On the basis of these results, the ignition probability for small, medium and large LP gas releases is 0%, 18%, and 52%, respectively. For large releases, approximately 36% of ignitions (19% of large releases) are instantaneous.

Table 5-4: Ignition Probabilities (%) for Small (less than 5 gal), Medium (5–100 gal), and Large (greater than 100 gal) Highway LP Gas Releases*

		Fire		Explosion and Fire	
Spill Size	**Total # of incidents**	**No.**	**%**	**No.**	**%**
Small	6	0	0	0	0
Medium	11	2	18	0	0
Large	21	11	52	4	19
Total	38	13	34	4	11

* As determined from HMIS database incident records from 1985 to 1995. Only those records that included comments are included in this table.

The UK Health and Safety Executive (1991) estimated ignition probabilities for rail transport of Gasoline and LPG based on release size as shown in Table 5-5. They suggested a much lower ignition probability of 3.3% for road transport of Gasoline and LPG based on 23 release observations with no ignition event combined with Poisson analysis at a 50% confidence level.

Table 5-5: Ignition Probabilities for rail transport of Gasoline and LPG (UK Health and Safety Executive 1991)

Substance	Type of ignition	Small spill	Large spill
Gasoline	Immediate	0.1*	0.2*
Gasoline	Delayed	0	0.1
Gasoline	None	0.9*	0.7
LPG	Immediate	0.1	0.2
LPG	Delayed	0	0.5
LPG	None	0.9	0.3

The ignition probabilities indicated by * are derived from "Actual" incidents, the remaining values has been estimated statistically

5.2.2 Proposed Ignition Probabilities

Rew et al (2000) argued that ignition probabilities of flammable gas clouds depend on the duration of the cloud. Some sources are intermittent in nature and other sources, such as hot surfaces, might become a potential ignition source only after a period of time. For example, if a steady state plume with roughly constant area within the flammability limits contains an ignition source that becomes active every 15 minutes, then the cumulative probability of ignition increases with time even though the cloud area does not increase. Finally, there is always the probability of an ignition source entering the cloud from outside its boundary.

None of the previously reviewed models demonstrated usefulness for application in our TDQRA module since they either did not consider the time element in estimating the ignition probability or require unavailable detailed information about ignition sources at the accident site. For this module, we propose a simple applicable approach to estimate ignition probability that takes into account release duration. Defining P_t^k as the probability of a cloud igniting at a particular time, *t*, then P_t^k is equal to the probability of a cloud igniting in the t^{th} time interval given that it did not ignite in the past *t*-1 time intervals. Assuming independency between the events, P_t^k is assumed to follow a discrete geometric distribution such that:

$$P_t^k = p_I^k (1 - p_I^k)^{t-1}, \qquad \textbf{(5-7)}$$

where p_I is a model parameter representing the probability of ignition within one time interval. Based on our judgment, we used a default ignition probability within one minute, p_I^k equal to 1% for Propane, and 0.05% for Gasoline. The estimated cumulative ignition probabilities using these default values are shown in Figure 5-9. The estimated cumulative ignition probabilities for 10 min and 120 min durations are given in Table 5-6Table 5-2.

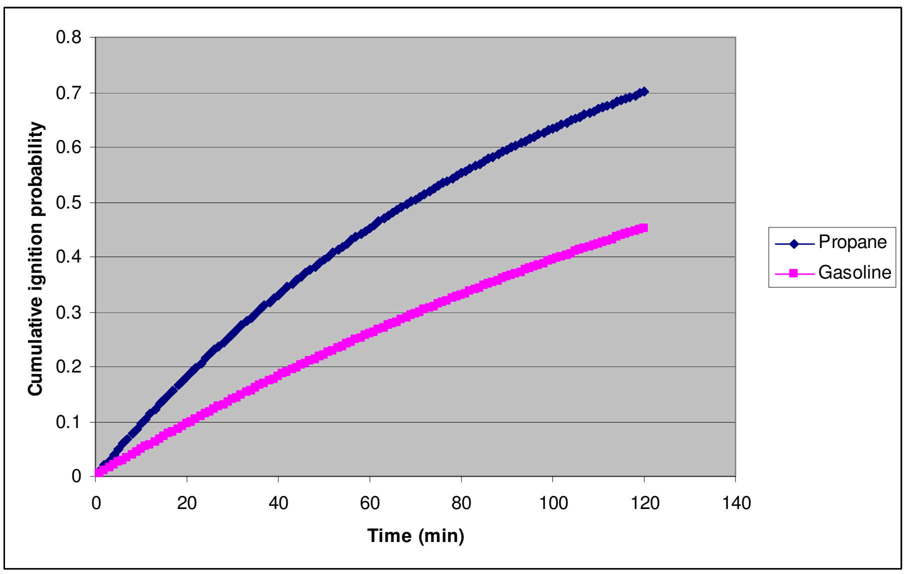


Figure 5-9: Estimated Gasoline and LPG cumulative ignition probabilities based on release duration

Table 5-6: Estimated Gasoline and LPG cumulative ignition probabilities for short and long release durations

Substance	Release duration (min)	Cumulative Ignition probability
Gasoline	10	0.05
Gasoline	120	0.45
LPG	10	0.1
LPG	120	0.7

5.2.3 Consequences calculation of Flammable Cloud Ignition

In case of ignition of a flammable cloud, exposure to flame and heat radiation will result in injuries or fatality. The time of exposure to heat radiation will affect the level of injury; however, the time element in the heat exposure is very short and was insignificant in our analysis. In modeling flash fire consequences, people caught in the fire boundaries are generally assumed to die and those outside the flame will likely survive (Rew et al. 1996). Accordingly, a lethality level of 100% is assumed within the vapor cloud and 0% outside of it. At time t_{ij}, consequences of the flammable cloud at point j when response is initiated from HazMat unit i, will be:

$$Csq_{ij}^{kr} = \sum_{t=1}^{t_{ij}} P_t^k * HA_{t_{ij}}^{kr} * pop_j \tag{5-8}$$

Where:

$HA_{t_{ij}}^{kr}$ is the hazard area within the LFL at time t_{ij} determined from gas dispersion modeling using ALOHA

pop_j is the population density at node j.

5.3 Consequences of Release of Flammable Liquids

Gasoline and other liquids are usually transported at atmospheric temperature and pressure. When Gasoline is released, the liquid partially evaporates and forms a flammable cloud above the released surface. For the modeling of Gasoline consequences, the released material is assumed to spread forming a pool with a depth of one centimeter

(US Environmental Protection Agency 1999). The discharge rate to air is estimated as the rate of evaporation from the pool.

The evaporated cloud may spread to the downwind direction depending on atmospheric conditions. When the flammable cloud reaches an ignition source, it will ignite and propagate backwards resulting in a pool fire. Although a pool fire is the final outcome once a Gasoline release has been ignited, the hazard area is not limited to the area of the pool, but instead expands to the flammable cloud area above the pool. As in the case of LPG flash fire, a lethality level of 100% within the vapor cloud and 0% outside of it are assumed.

We modeled the evaporation of Gasoline and the formation of a flammable cloud above the released pool using ALOHA. Gasoline is not part of ALOHA hazardous material library; however, it was added to the ALOHA chemical library manually. Ignition probabilities and consequences estimates were carried out according to sections 5.2.2 and 5.2.3.

5.4 Environmental Impact

QRA models commonly use the number of fatalities and injuries as a measure of consequences (see Organization for Economic Co-operation and Development 2004 and Health and Safety Executive 1991). Moreover, the assumption is usually made that other consequences will be in proportion to the number of fatalities and injuries. However, many historical accidents indicate that this assumption might be incorrect. Depending on location and conditions at the time of release, discharged material could destroy wildlife and vegetation, escape to nearby waterways and drainage systems, penetrate the soil, and contaminate ground water and wells. Thus, the impact of HazMat releases into the environment can be horrendous as was the case of the 1991 California train derailment that spilled approximately 20,000 gallons of pesticide into the Sacramento River (Anderson 1991).

However, assessing the effects of HazMat releases into the environment is difficult to say the least. Data is usually limited and the factors affecting the outcomes of a release are complex. In many cases establishing the final and complete impact of Hazmat releases on the surrounding environment is not possible. Thus, in such circumstances, assessing the likelihood of identified concentrations of concerns occurring in the air, water, and soil may be more appropriate (Nicolet-Monnier and Gheorghe 1996).

Models for HazMat environmental impact consequence analysis are usually site specific, where detailed information about site topography, soil characteristic, distance to groundwater, and distance to nearby waterways can be obtained. However, in case of HazMat road transport, accidents can occur at any point on the network, and thus accident locations, and hence site specific information, are not known. For this reason, such site specific environmental risk assessments were deemed unsuitable for use with our model.

This section is aimed at a preliminary investigation of the environmental impact of HazMat releases and is not meant to be a detailed evaluation of environmental impact. Instead, the following research functions as an initial investigation on what the impact might be. In general, environmental impacts of HazMat releases are assumed to be proportional to the amounts released. For our module, a simple approach is used to evaluate the environmental impact of HazMat releases, where the impact on the environment is assumed to be *linearly* related to the amount of HazMat released. Moreover, an environmental impact index was used as an environmental consequence measure. This index is meant to represent impact on existing vegetation and wild life, long-term effects, and clean-up as well as rehabilitation costs. Finally, different weights were assumed for different HazMat types depending on their perceived impact.

Defining $REnv_{ij}^{kr}$ as the environmental risk from a release type *r* of HazMat type *k* at node *j* when HazMat team at node *i* responds to the release, $REnv_{ij}^{kr}$ is calculated as follows:

$$REnv_{ij}^{kr} = Frq_{j}^{kr} * EnvCsq_{ij}^{kr} \tag{5-9}$$

Where

Frq_{j}^{kr} is the frequency of release of HazMat type *k* and releases rate *r* at node *j*

$EnvCsq_{ij}^{kr}$	is the environmental consequence at node j due to release type r of HazMat type k when a HazMat team at node i responds to the release.

$EnvCsq_{ij}^{kr}$ is calculated as follows:

$$EnvCsq_{ij}^{k} = DR^{kr} * t_{ij} * W^{k} \tag{5-10}$$

Where:

DR^{kr}	is the discharge rate of release type r for HazMat type k in kg/min (Table 3-6)
t_{ij}	represents response time from HazMat teams at node i to the release site at node j, in minutes
W^{k}	represents weight of the environmental impact of release of one ton of HazMat type k

Finally, the environmental risk at node j when response is initiated from HazMat team at node i is calculated according to the following equation:

$$REnv_{ij} = \sum_{k}\sum_{r} REnv_{ij}^{kr} \tag{5-11}$$

Values of W^{k} for different types of HazMat were judged according to their perceived environmental impact. Different types of HazMat will have different impact severities on the environment within the vicinity of the release site. In general, fire hazards are of less relevance to the environment in comparison to the acute and chronic toxicity impacts from the release of toxic materials, while the ignition of flammable substances results in destruction of vegetation and wild life within the hazard area. The analysis of flammable hazard is limited to fire due to the HazMat within the LFL concentration. The case of forest fires, as a result of HazMat ignition expanding beyond the hazard area, will not be considered.

Toxic gas releases destroy wild life and affect vegetation, and their cloud area is much larger than that for flammable gases. While gases evaporate upon release, resulting in no permanent residue in surrounding ground or nearby waterways, released liquid HazMat can penetrate the soil, escape to nearby waterways and affect the surrounding environment for much longer periods of time. Among different HazMat types, toxic liquid releases affect the environment the most.

Table 5-7 shows assumed weights for environmental impacts of release of different HazMat for each ton released. These values were based on our judgment and may not reflect the actual environmental impacts of HazMat releases.

Table 5-7: Environmental risk impact weight for different types of HazMat

HazMat type	Weight of environmental impact
Flammable gases	1
Toxic gases	5
Flammable liquids	10
Toxic liquids	100

Locating HazMat teams based solely on environmental risk is unrealistic. However, combining human fatality and environmental risks is not an easy task. Nicolet-Monnier and Gheorghe (1996) suggested that public health risk should be assessed separately from environmental risk. Consequently, given the fact that the absolute value of quantitative risk estimates is highly questionable, trying to combine human fatality estimates and environmental impact estimates is practically meaningless. Therefore, these two measures will be considered separately.

5.5 Summary

Consequence modeling of considered HazMat types was discussed in the chapter with the considered release outcomes for various HazMat releases as follows: toxic cloud for an Ammonia release, flash fire for a Propane release, and ignition of the vapor cloud above the pool for a Gasoline release. A simple environmental impact index is suggested for the preliminary investigation into the environmental impact of HazMat releases.

CHAPTER 6: CASE STUDY

This Chapter describes a case study to illustrate the relevance of the risk-based HazMat team location optimization model as a tool in emergency response planning. In this case study, part of the southwestern Ontario region (shown in Figure 6-1) will be used as an example to illustrate the features and potential applications of the developed model.

Figure 6-1: Southwestern Ontario area covered by case study

The optimal location solution for a given number of HazMat teams is defined as the solution which gives the minimum total network risk while ensuring that maximum response time to any node on the network does not exceed a preset threshold. For this case study a maximum response time threshold of 60 minutes was used. The problem to be solved is minor in scope; hence complete enumeration was used to achieve the solution. The model is run for the whole location solution domain to reach the optimal location solution.

6.1 Case Description and Input Data

The study area covers a total of 1040.274 km of highways and has a total annual truck traffic of 2,147,274 truck-km. The road network is represented as a directed graph with nodes and links. A simple network that consists of 32 nodes and 92 links is used to illustrate how to use different aspects of the developed model with the following node attributes included: node ID, longitude, latitude, population density (inhabitance/ km), host Fire station (0=no, 1=yes), and within urban area (0 = no, 1 = yes). Link attributes include parameters such as link ID, head node ID, tale node ID, length (km), posted speed (km/hr), and average annual daily traffic (AADT).

Figure 6-2 illustrates the model representation of the road network, fire stations, HazMat team locations, links and nodes on the considered region. Numbers on the graph represent node numbers.

Digital representation of the road network is provided by the "Atlas of Canada," Natural Resources Canada. The data is downloaded from the GeoGratis (2004) web site: National Atlas Base Maps. Base map components are available in five scales and in a number of data exchange formats, and include major road and rail transportation networks.

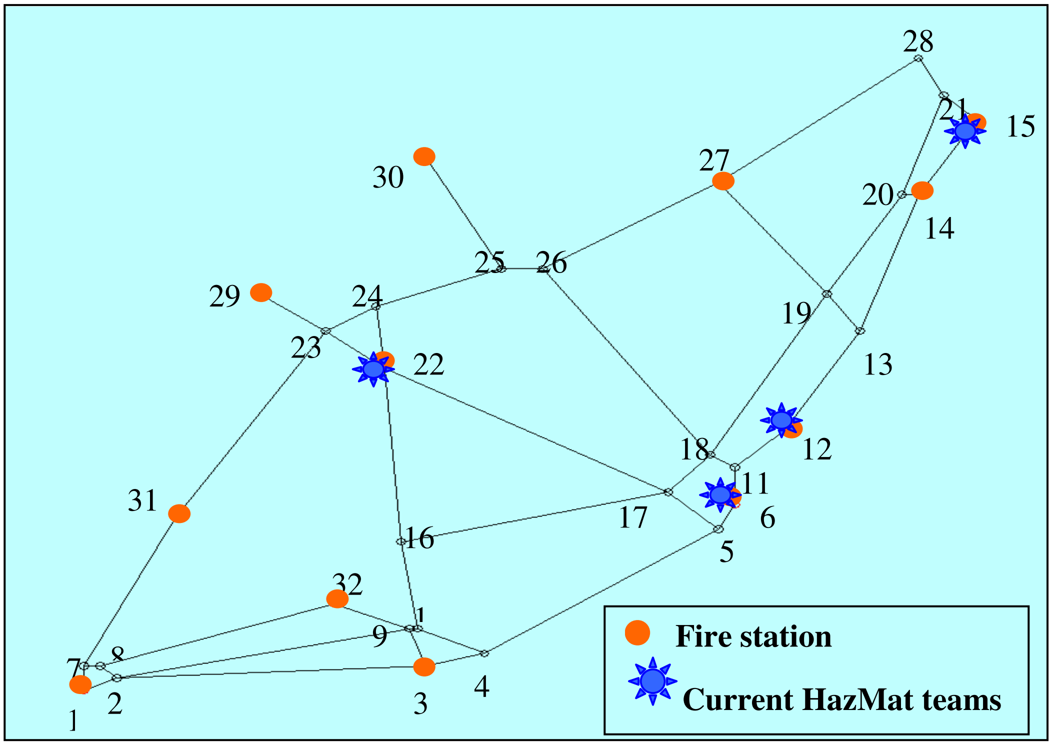


Figure 6-2: The HazMat location model representation of the case study area

Data for the case study area was extracted from National Atlas Base Maps files and processed to a text file format compatible with the requirements of our model.

6.1.1 Existing Locations of Fire Stations and HazMat Teams

There are a total of 520 fire departments in Ontario, 167 of which are full time fire departments with the remaining 353 classified as volunteer. The twelve full time fire departments within the study area are located at Paris, Brantford, Oakville, Burlington, Milton, Hamilton, Drumbo, Cambridge, Kitchener, Guelph, Mississauga, and Woodstock. Of these twelve fire departments, only four have HazMat teams, namely Mississauga, Hamilton, Burlington, and Cambridge[9].

Mississauga Fire and Emergency Services have three crews that are trained at the technician level and one specialty vehicle equipped to carry all HazMat team tools and supplies. The Cambridge Fire Department presently has ten fire fighters trained at the technician level, six of which are certified to deliver training to the operations level. The department has two apparatus which carry equipment related to a HazMat response and is also presently involved with the Kitchener and Waterloo fire departments in developing a cooperative assistance response for the area of Waterloo Region. The Hamilton Fire Department has been providing HazMat response since the mid 70's. The present team is made up of 40 members with a minimum of seven members of the team trained at the Technician Level and continuously on duty. The team members staff two vehicles and have provided regional emergency response since the early 80's.

Although there are differences in the level of available HazMat response capabilities among these fire departments, for the purpose of this research the assumption is made that all of them carry the same capabilities. In addition to the previous HazMat teams the Brantford, Oakville and Guelph fire departments provide some level of HazMat response. However, because of the low level of HazMat response available at these locations, they we not considered in the case study.

[9] Personal communication(email) with different fire departments

6.1.2 Response Time

In this research, response time is defined as the time elapsing from release occurrence until mitigation measures are applied at the scene. Following this definition, response time has three components: dispatch time at the station, travel time from the station to the site, and mitigation time. Response to a release on the road network is assumed to come from the nearest HazMat team with response time to different nodes obtained using fastest route calculations.

Emergency vehicles travel time is a function of various factors including, but not limited to, travel distance, the layout of the region, weather conditions, road and traffic conditions. Emergency vehicles may experience a delay especially in the case of a highly congested network, highway closure due to an accident, or while passing through a town at a posted lower speed. Several methods of representing travel times on links were investigated with the following options considered:

- Using free flow travel time assuming that emergency vehicles would have the right of way and would experience no delays while traveling on the road network.
- Using average travel time assuming that emergency vehicles would travel at the same speed as other vehicles.
- A compromise of the previous two assumptions, where the emergency vehicles are assumed to experience some delay on the road network but not as much as other vehicle delays.

For the case study, the emergency vehicles are assumed to be delayed by a certain percentage of the free flow travel time (called the “delay factor”). Free flow travel time is calculated using posted speed and link length. Using a delay factor of “1” will result in travel times equal to the free flow travel time. As a result, the higher the delay factor, the longer calculated travel times on links will be. Moreover, emergency vehicles were assumed to experience a delay at each intersection node either due to passing through an urban area, changing direction, or getting onto or off ramps. Intersection delay time is assumed to have a linear relationship with population density at each intersection node with a maximum default value of 2 minutes for heavily populated areas such as Mississauga and Hamilton (population density of 700 inhabitant/km^2). The model allows investigation of different input parameters but default values are set to a 1.2 delay factor, 3 minutes for assembly time, 5 minutes for mitigation time, and 2 minutes for maximum intersection delay.

6.1.3 Meteorological Conditions

The atmospheric dispersion of vapor clouds depends on the meteorological conditions at the time of release. Wind speed and atmospheric stability are the primary factors that influence dispersion. Average wind speed values and direction for the case study area were obtained from Environment Canada (2004), and the weather network (2004) websites. After investigating the norms for different weather stations within the region, winds of 17.5 km/hr blowing from the west were found to best represent average conditions over the whole region. Figure 6-3 shows the mean wind speed for southern Ontario (Energy Educators of Ontario 1993). Other assumptions include D wind stability, ground roughness equivalent to open country, partly clouded skies, and an air temperature of 21 C. Table 6-1 summarizes different default parameters used in the TDQRA module.

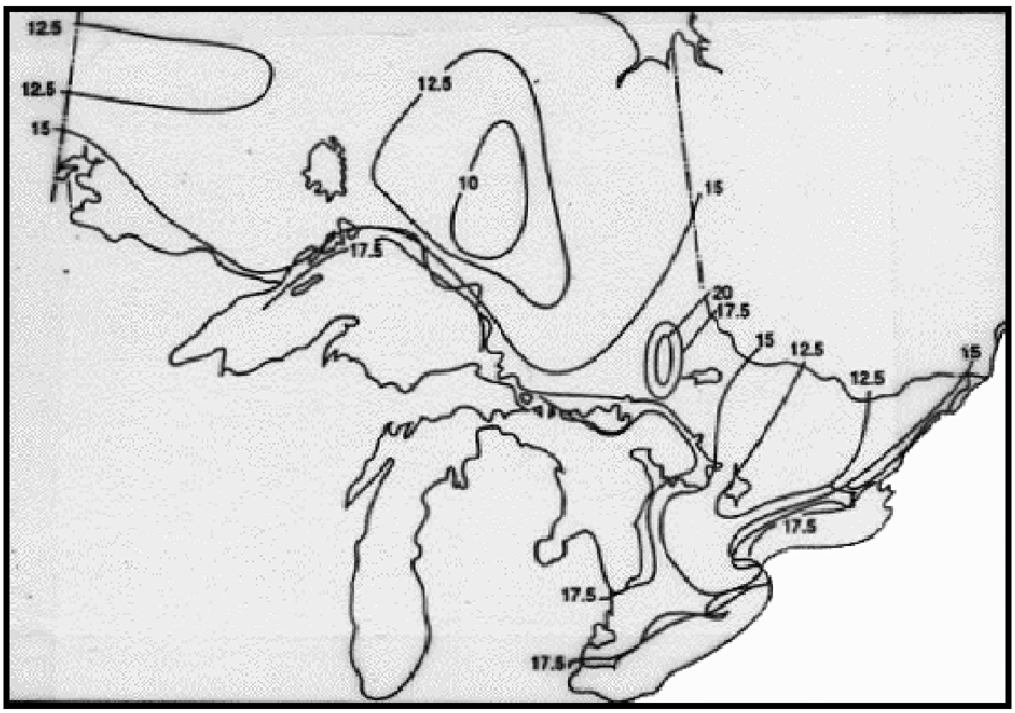


Figure 6-3: Mean wind speed map for southern Ontario (wind in km/hr)

6.1.4 Population Distribution

Population density distribution over the region was obtained from Canada 2001Census data (Statistics Canada 2003). Population densities are given at Census Subdivisions level. Figure 6-4 shows southern Ontario population distributions for 1996 (Brock University map library 2004).

Table 6-1: Assumed model parameters

Response time	
Dispatch time	3 minutes
Travel time	assumed travel times on links as 120% of free-flow travel times (20% to account for delays)
Mitigation time	5 minutes
Intersection delay	Maximum of 2 minutes
Weather conditions	
Wind speed	17.5 km/hr
Wind direction	West
Wind stability class	D
Air temperature	21^{o}C
Relative humidity	50%
Cloud cover	50%

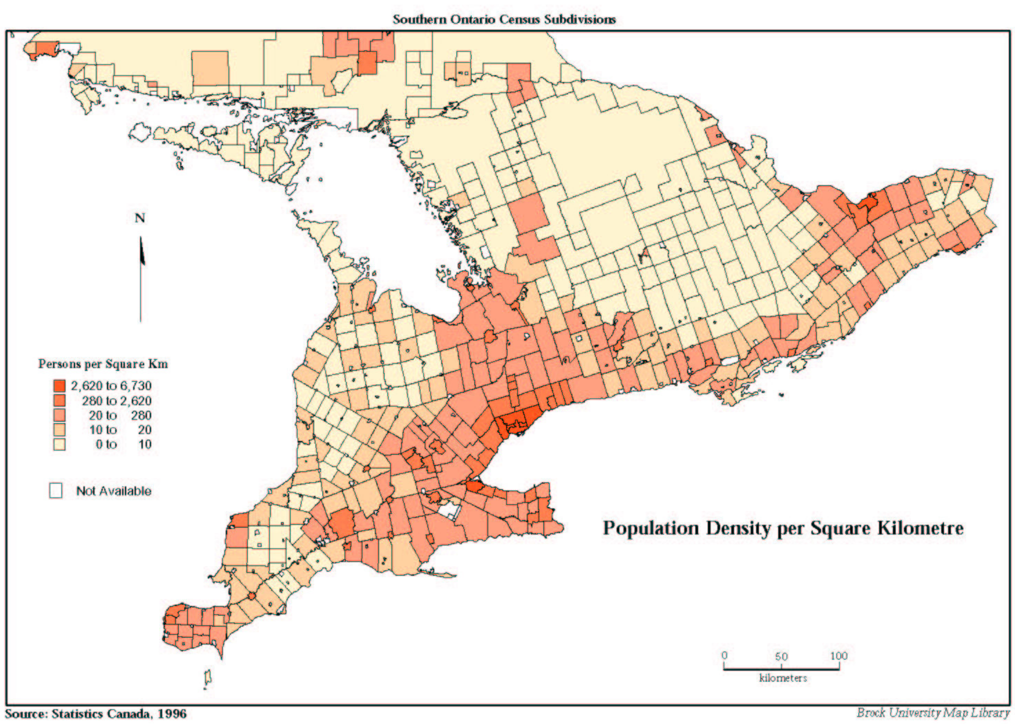


Figure 6-4: Southern Ontario Population distributions

6.1.5 HazMat types and Discharge Rates

Four HazMat types are considered for the TDQRA module, namely toxic liquefied gases (represented by Ammonia), flammable liquefied gases (LPG represented by Propane), flammable liquids (represented by Gasoline), and toxic liquids. For each HazMat type, two release types are considered—spill and leak—and two release quantities are considered: large and small. Discharge rates estimated from DGAIS data (Table 6-2) are used for this case study. Estimation of these values were discussed in Section 3.3.

Table 6-2: Discharge rate for different scenarios (kg/min)

	Discharge rate (kg/min)				
	Flammable LPG	Toxic LPG	Flammable liquids	Toxic/corrosive liquids	average release duration (min)
Ave small spill	4.7	9	12.7	6.3	15
Ave large spill	645.3	336	626	717.1	15
Ave small leak	0.6	0.06	1.9	0.9	60
Ave large leak	121	35	92	98.2	60

6.1.6 HazMat Traffic Volumes

Estimates of HazMat traffic volumes were based on available truck Average Annual Daily Traffic (AADT). Moreover, total HazMat movements were assumed to constitute a fixed percentage of the total truck AADT on links. The truck AADT for the considered network was obtained from the Ontario freight transportation system study (Ray Barton Associates et al. 2000). Furthermore, traffic volumes for different types of HazMat were assumed to be proportional to the overall representation of these types in the overall HazMat movements.

Estimates of the share of HazMat movements in total truck traffic for different HazMat classes were based on the “1995 Road Side Survey” data (Canadian Council of Motor Transport Administrators coordinates 2002). Using the “1999 National Roadside Study” we estimated 9.85% of the total truck movements in Canada to be HazMat related. Percentages of different HazMat types transported in Canada as obtained from Transport Canada (2002) are shown in Table 6-3. Applying these estimates to the truck Annual Average Daily Traffic (AADT) on individual links gives the HazMat traffic volumes by HazMat type.

Table 6-3: Percentage of different HazMat types transported by road (by tonnage)

HazMat type	Percentage of total HazMat
Flammable liquids (Gasoline)	64.61%
Toxic liquids	14.62%
Flammable liquefied gases (Propane)	3.58%
Toxic liquefied gases (Ammonia)	0.98%

6.1.7 Estimates of Release Probabilities

Table 6-4 lists release probabilities for different release scenarios. Values in this table were calculated from Button’s (1999) conditional release probability estimates using Ontario load size and accident outcome probabilities as discussed in Section 4.3.

Table 6-4: Release probabilities (%) given an accident has occurred

HazMat type	Ammonia	Propane	Gasoline	Toxic liquids
large spill	0.87	1.09	1.34	0.56
small spill	0.44	0.55	0.73	0.28
large leak	0.08	0.10	0.12	0.05
small leak	0.19	0.24	0.30	0.12
total	1.58	1.98	2.49	1.02

Accident rates were obtained for large tanker trucks using the Ontario Accident Data system (ADS) for the years 1988 to 1992 (Saccomanno et al. 1998). These rates expressed on per MVKm bases are summarized in Table 6-5 for three types of highways.

Table 6-5: Truck accident rates (accident/MVKm)

Highway type	Urban	Rural	Arterials	Overall
Accident rate (accident/MVKm)	1.023	0.549	1.003	0.924

For this case study we used an overall truck accident rate of 0.924 accident/MVKm for all types of highways. Combining release probabilities from Table 6-4with the accident rates from Table 6-5 yields the frequency of release on a per MVKm bases.

6.2 Sensitivity Analysis

The developed HazMat location model includes a large number of parameters and input variables that are uncertain and cannot be predicted precisely. A range of values or a probability distribution might exist for each input parameter due to the lack of sufficient data, precise values or an uncertainty in the HazMat release process itself because of system variations over time and space. One common treatment of such variations in values is to use the mean value of each parameter or variable, assuming that the impact of uncertainty on the final solution is negligible. However, using average values might introduce a significant error to the evaluation process. For example, using an average wind speed value of 17.5 km/hr blowing from the west might result in significantly different results compared to the modeling of a wind rose *with* different probabilities for different wind speeds and directions. When values are averaged within a rather narrow range, errors due to averaging are small enough to ignore. However, when values are significantly different the average error might become substantial.

In this Section we investigate the effects of uncertainty in input parameters on the performance of the developed model. We also examine different values for each input parameter and how the resulting HazMat locations change.

6.2.1 Accident Frequency

In the developed model, an overall average truck accident rate of 0.924 accidents/MVKm was assumed for all links. Under such an assumption, uniform change in accident rate values for all links will have no effect on the choice of the optimal solution since risk estimates are linearly related to the point estimate value of the accident rate.

In this section, simulation is used to assess the impact of accident rate variation for different links on the choice of optimal HazMat team location. Accident rate on each link was assumed to follow a normal distribution with a mean value μ equal to 0.094

accidents/MVKm, and a standard deviation σ. Different values for the variation of accident rates on links (σ/μ) were assumed by varying the standard deviation, σ. Using different σ/μ values, we generated different accident rates on links and ran the model to determine how many times the current optimal solution would hold its position. Figure 6-5 shows that a 25% variation in the truck accident rate demonstrated almost no change in the choice for an optimal solution, while a variation of 50% caused a 6.6% change in the choice for an optimal solution. As the variation of accident rate increases to 75%, the change in the choice of optimal solution increases to 25.5%.

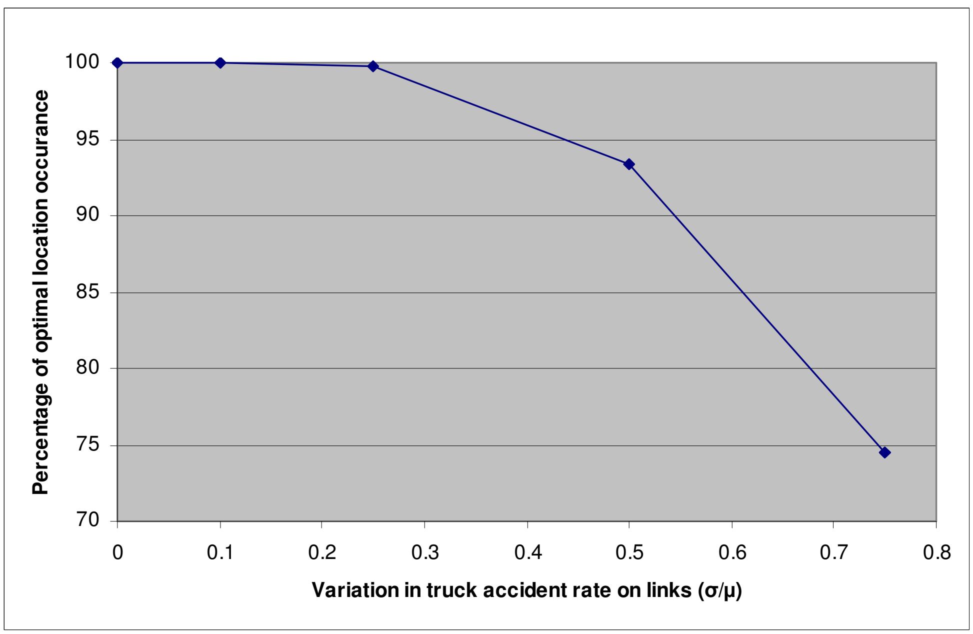


Figure 6-5: Variation in optimal location results with variation in truck accident rates on links

6.2.2 Release Probabilities

The model uses default release frequencies shown in Table 6-6. These values were derived from Button's (1998) estimates of conditional release probabilities, as illustrated in section 4.3. In this section, we will compare results using the default values to results using earlier estimates by Saccomanno et al. (1989). Their estimates of different release type probabilities given a release and the probability of a release given an accident were combined. The resultant release probabilities given an accident for different release types are shown in Table 6-7.

Table 6-6: Default release probabilities for different HazMat types and different release scenarios (%)

HazMat type	large spill	small spill	large leak	small leak	total
1 (Chlorine)	0.872	0.438	0.077	0.194	1.582
2 (LPG)	1.091	0.546	0.096	0.243	1.976
3 (Gasoline)	1.342	0.729	0.119	0.299	2.489
4 (Toxic liquids)	0.560	0.280	0.050	0.125	1.015

Table 6-7: Release probabilities given an accident (%) by release type, based on Saccomanno et al. (1989) estimates

	P (release type | accident)						
	Instant			Continuous			total
	high	medium	low	High	medium	low	
Chlorine	0.288	0.352	0.496	0.192	0.128	0.144	1.6
LPG	0.37	0.74	0.74	0.148	0.592	1.11	3.7
Gasoline	4.8	0	7.2	0	0	0	12

In the developed TDQRA, HazMat releases are classified into large and small only. Therefore the release probabilities in Table 6-7 needed to be adjusted in order to be used in our model. We assumed “instant” and “continues” releases would represent “spills” and “leaks,” respectively. “High” and “low” releases would be equivalent to “large” and “small” releases, respectively. Half of the “medium” release probability was assigned to the “high” release, while the other half was assigned to the “low” release. The adjusted “high” and “low” release probabilities were assumed to be equivalent to large and small release probabilities, respectively. Table 6-8 shows the adjusted percentage of probability of release for different release types.

Table 6-8: Adjusted release probabilities (%), based on Saccomanno et al. (1989) estimates

HazMat type	large spill	small spill	large leak	small leak	total
1 (Chlorine)	0.464	0.672	0.256	0.208	1.6
2 (LPG)	0.74	1.11	0.444	1.406	3.7
3 (Gasoline)	4.8	7.2	0	0	12

We ran the model for both release probability estimates in Table 6-7 and Table 6-8. The risk and location results in Table 6-9 show a substantial difference in risk estimates using the different release probability estimates. Total network risk using Saccomanno et al. (1989) estimates are more than double the estimates using model default values, while the difference in maximum risk estimates is even higher. However, no change in the optimal locations of HazMat teams may be found. Also, ranking of current locations among best solutions was slightly changed from the 59th to the 58th place.

Table 6-9: HazMat teams optimal locations and total risk results for different release probabilities estimates

Release probabilities	HazMat teams optimal locations				Tot risk (fatality/yr)	Max Risk (fatality/yr)	Max response time (min)
Model defaults	6	14	22	27	0.0372	0.0067	50
Saccomanno et al. (1989) values	6	14	22	27	0.0914	0.0170	50

Results show that while varying accident and release rates uniformly for the whole network affect estimated risk values, they do not affect the choice of optimal solution and have no or minimal effect on the ranking of current solution among different alternatives.

6.2.3 Response Time

Response time consists of three components: dispatch time at the team location, travel time to the release site, and mitigation time at the release site. Default values for dispatch and mitigation time are set at three and five minutes respectively. Change in response time for two different ways is investigated: change by a constant value and change by a certain percentage. Change by a constant value is applicable to estimates of dispatch and mitigation times, while change by certain percentage is applicable to delays in travel times.

Four values of combined dispatch and mitigation time were tested: the default of 8 minutes, along with 15, 20, 30, and 60 minutes respectively. Results are shown in Figure 6-6 and Table 6-10. The results show that total risk on network increases with the increase in dispatch and mitigation time. The increase is almost linear for values up to about 25 minutes and levels off for larger dispatch and mitigation time values. However, this outcome was expected as a maximum spill time of 30 minutes and a maximum leak time of 2 hours were established for the case study. Higher values of response time will have no effect if the release reaches its maximum point.

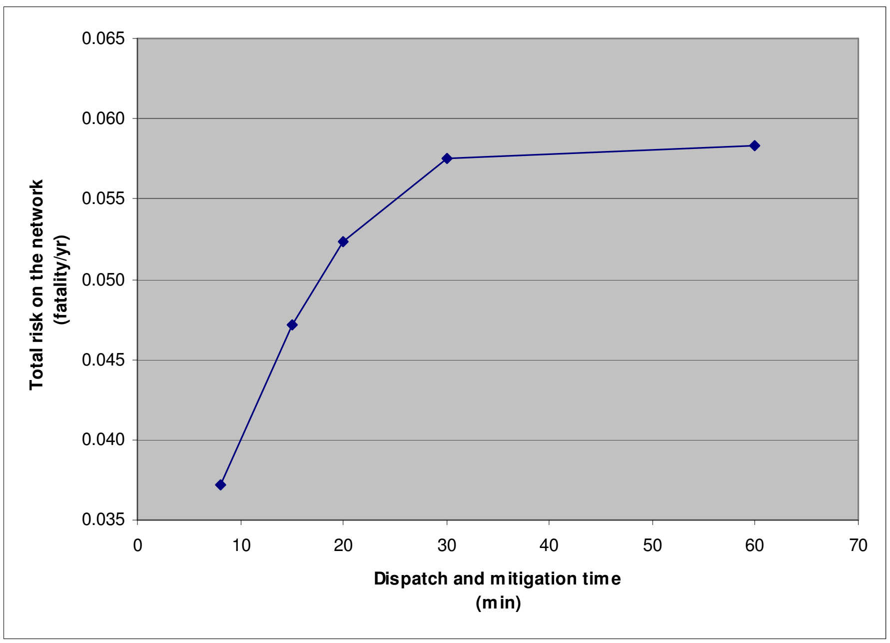


Figure 6-6: Change in total network risk for different dispatch and mitigation times

Table 6-10: Location and risk results for different dispatch and mitigation times

Dispatch and mitigation time	HazMat teams optimal locations				Tot risk (fatality/yr)	Max Risk (fatality/yr)	Max response time (min)
8 min	6	14	22	27	0.0372	0.0067	50
15 min	6	14	15	27	0.0472	0.0072	71
20 min	6	14	15	27	0.0523	0.0074	76
30 min	6	14	22	27	0.0576	0.0074	72
60 min	6	14	22	27	0.0583	0.0075	102

For combined dispatch and mitigation time values of 15 and 20 minutes, the optimal solution was found to favor high population locations (node 15), while for smaller and larger values, locations towards the geographical center of the region are more favorable (node 22). Furthermore, for dispatch and mitigation times of 15 and 22 minutes, the current solution was found to be less favorable, ranking 68 and 115 among the best alternatives (down from 52nd with 8 minutes dispatch and mitigation time). However, for longer dispatch and mitigation times the current solution again becomes more favorable, ranking 46th among best alternatives for 60 minutes of dispatch and mitigation time.

In addition, emergency vehicles are assumed to be delayed by a certain percentage of the free flow travel time (called “delay factor”). Using a delay factor of “1” will result in travel times equal to the free flow travel time. Moreover, the higher the delay factor is, the longer the calculated travel times on links will be. The sensitivity of the risk estimates and the location solution to the value of the delay factor is examined by running the model for different values of the delay factor. As a result, the total risk was found to increase with the increase in the delay factor as shown in Figure 6-7, while results in Table 6-11 show that optimum HazMat team locations differ for larger delay factors. Node 15 (Mississauga) becomes more favorable than node 22 (Cambridge) for delay factor values over 1.4. Moreover, from Figure 6-7 we noticed that the relationship between risk estimates and the delay factor is linear for the same location solution with the change of slope at the delay factor value of 1.6 due to the change in the optimal solution.

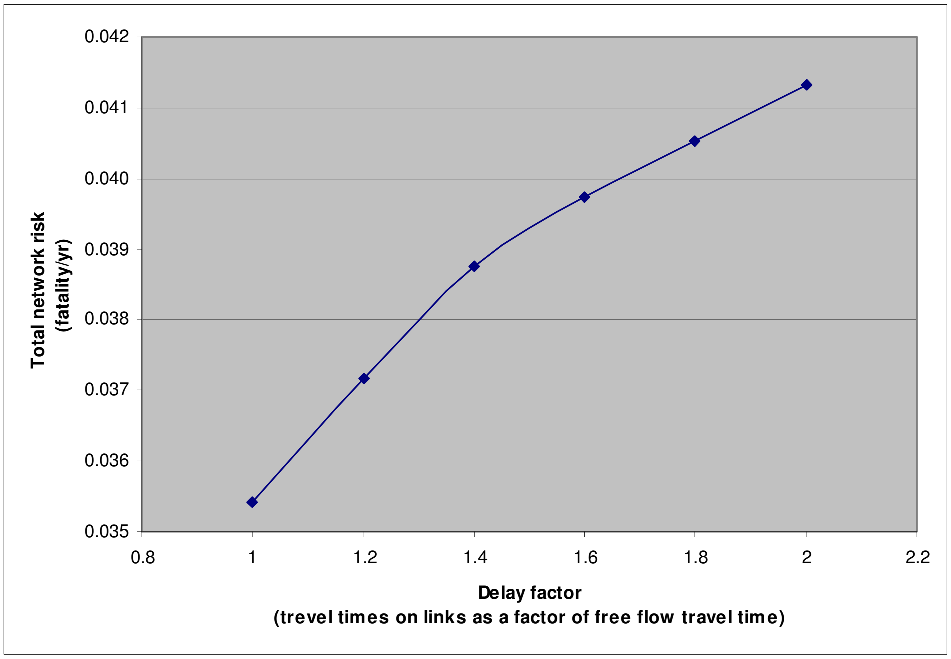


Figure 6-7: Effect of change in the delay factor on total risk on the network

Table 6-11: Location and risk results for different delay factors

Delay factor	HazMat teams optimal locations				Tot risk (fatality/yr)	Max Risk (fatality/yr)	Max response time (min)
1	6	14	22	27	0.0354	0.0061	43
1.2	6	14	22	27	0.0372	0.0067	50
1.4	6	14	22	27	0.0387	0.0071	56
1.6	6	14	15	27	0.0397	0.0063	82
1.8	6	14	15	27	0.0405	0.0066	90
2	6	14	15	27	0.0413	0.0069	99

6.2.4 Variations in Travel Times on Links

The HazMat team locations model uses deterministic travel times on links. In this section we use simulation to study the effect of variation in real links travel time on the optimality of the chosen HazMat team locations.

Real travel time on each link was assumed to follow a normal distribution with a mean value μ equal to free-flow travel time multiplied by the delay factor, and a standard deviation σ. Different values for the variation of travel times on links (σ/μ) were assumed by varying the standard deviation, σ. Using different σ/μ values, we generated different travel times on links and ran the model to determine how many times the current optimal solution would hold its position. Figure 6-8 shows that for variation in travel times of 10% there was slight change in the choice of the optimal solution in 0.3% of the times and for a variation of 15% there was a 3.2% change in the choice of the optimal solution. As the variation in travel time reached 25% there was a 14.4% change in the choice of the optimal location.

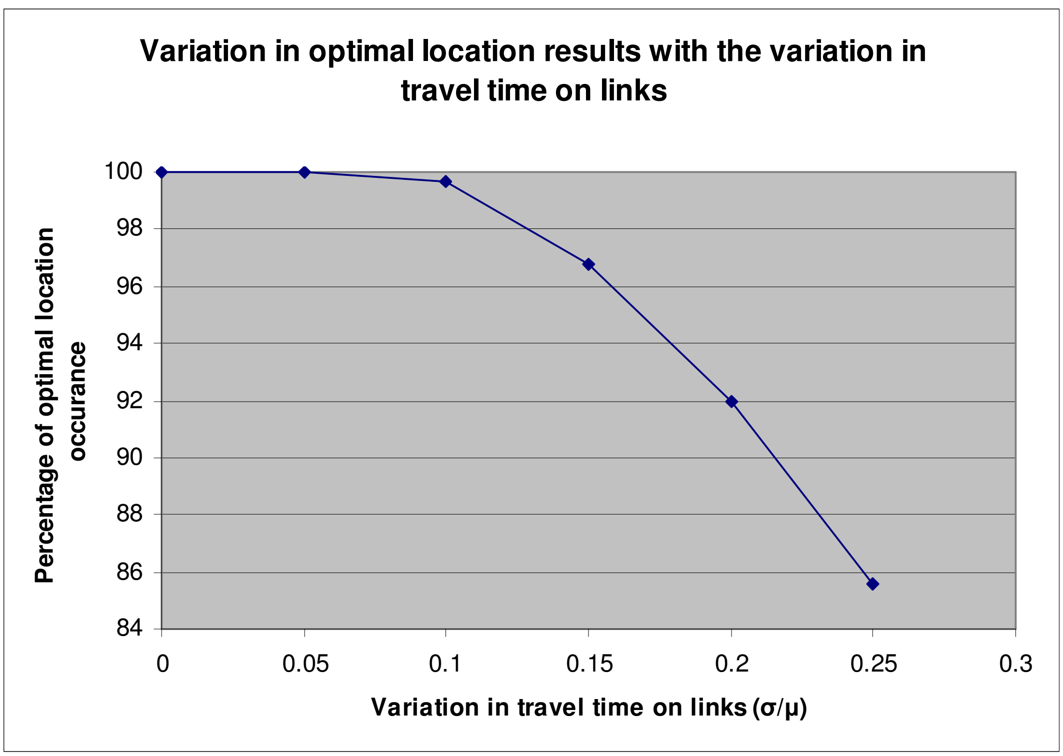


Figure 6-8: Variation in optimal location results with variation in travel time on links

6.2.5 HazMat Volumes

Due to lack of data, major assumptions have been made for HazMat volumes and the routes on which these volumes are transported. HazMat volumes are assumed to constitute a certain percentage in the total truck traffic on links. For Canadian highways, a value of 9.85% HazMat traffic in the total truck movements was obtained using the commercial vehicles road side survey (1995)[10]. Sensitivity of the model to variation in HazMat volume on links is examined by simulating HazMat volumes as a normal distribution. Results in Figure 6-9 show that for a variation of up to 30% in the HazMat volumes, there is a slight change in the choice of the optimal solution and as the variation increase to 50% the change in the optimal solution choice increases to 3.2%.

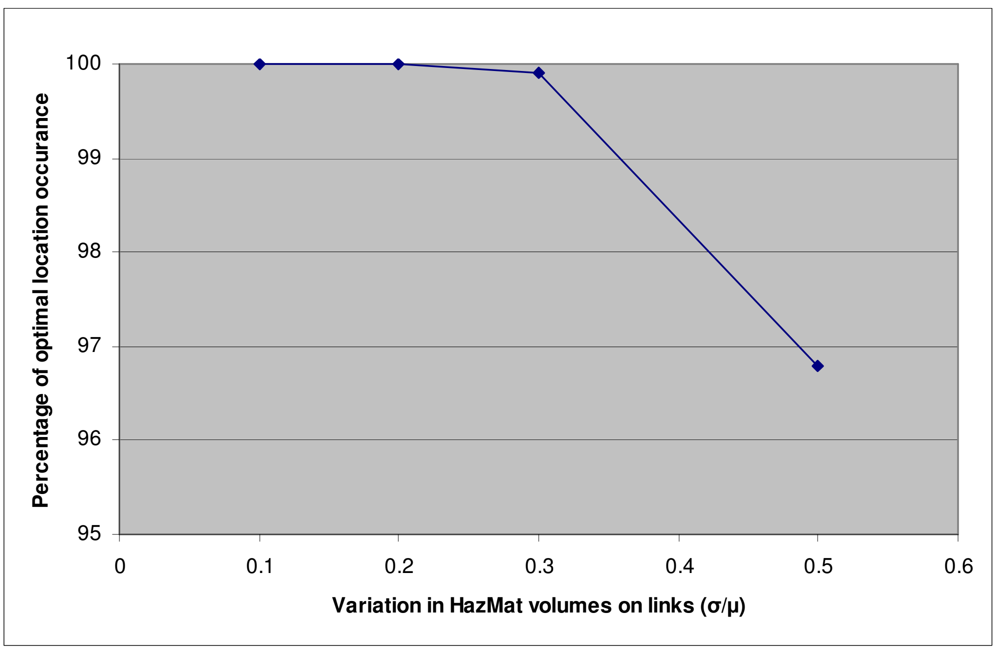


Figure 6-9: Variation in optimal location results with variation in HazMat volumes on links

[10] commercial vehicles road side survey (1995)

6.2.6 HazMat Routes

In the southwestern Ontario case study, detailed data about actual HazMat routes was not available. Thus, the assumption was made that HazMat are being transported on all links in proportion to truck movements. However, a different assumbtion could be that all HazMat are transported on the two main corridors in the region, namely 401 and QEW (and part of 403 between Mississauga and Hamilton). Highway 401 is a main transportation corridor while QEW carries most of the shipments from eastern Canada to the USA cross-border at Niagara Falls.

The model was used to investigate results sensitivity to the different routing assumption.

Table 6-12 shows that the effect of different routing methods on total risk estimate is relatively small; however the location of the optimal solution differs for the two routing methods. Thus, if all HazMat movements are routed through 401 and QEW, HazMat team locations at Burlington (node 12) and Mississauga (node 15) become more favorable than Hamilton (node 6) and Oakville (node 14).

Table 6-12: Four HazMat teams optimal locations for the 2 different routing strategies

Strategy					Tot risk (fatality/yr)	Max Risk (fatality/yr)	Max response time (min)
Optimal location for HazMat movements on all links	6	14	22	27	0.0372	0.0067	50
Optimal location for HazMat movements on 401 & QEW	12	15	22	27	0.0365	0.0088	50

6.2.7 Level of Aggregation

Aggregating accident and release frequencies on links to adjacent nodes introduces an error to the risk estimates and, hence, to the choice of the optimal HazMat team locations. This section is aimed at investigating and illustrating such errors and how they might influence the location process. Figure 6-10 shows the network representation, node aggregation, and link lengths used initially as well as the current and optimal solutions. The network contains long links with the longest (32 km in length) running between node 2 and 3.

The maximum aggregation error on the network is introduced by the longest link (link 2 between node 2 and 3). However, adding a hypothetical node on link 2 to divide it into two shorter links with lengths of 16 km each and re-running the model gives significantly different results. The new optimal solution (Figure 6-11) puts less emphasis on the southeastern part of the considered case study area and favors the further to the north-east location of Mississauga (node 15) over Oakville (node 14) and the further to the north location of Kitchener (node 29) over Cambridge (node 22) with a total network risk of 0.0371 fatalities per year and a higher maximum response time of 58 minutes.

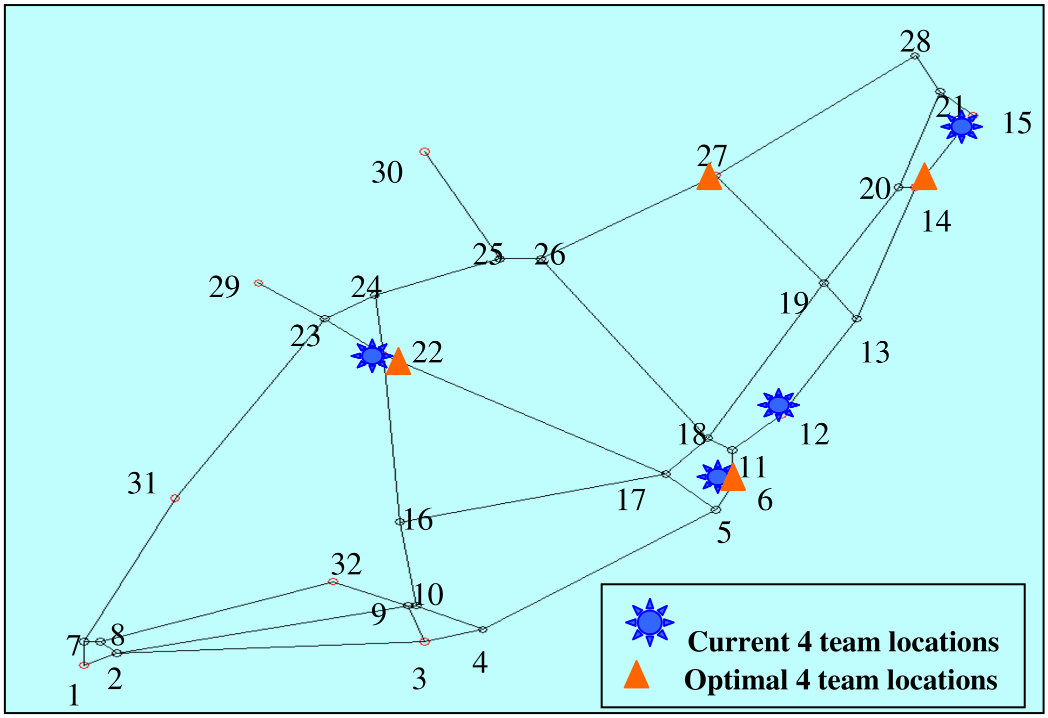


Figure 6-10: Current and optimal location solutions using initial network with 32 nodes (network 1)

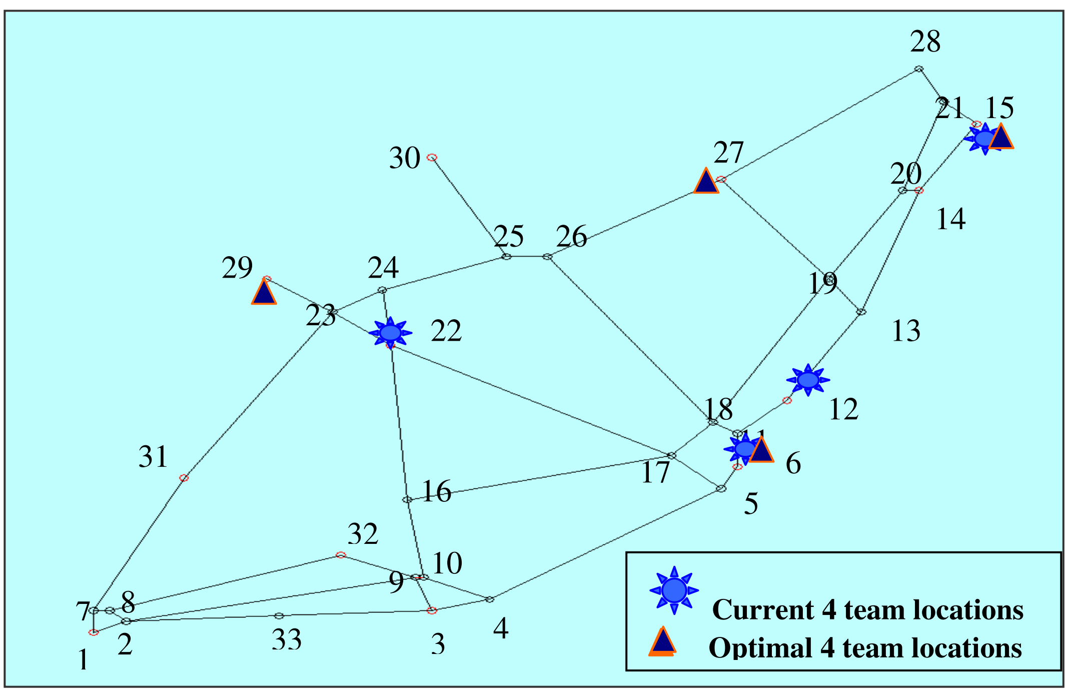


Figure 6-11: Current and optimal location solutions when adding hypothetical node 33 (network 2)

This solution is the optimal solution for a maximum response time of 60 minutes; however, notwithstanding the maximum response time constraint, the risk minimizing solution is at nodes 12, 15, 27, and 29 with a lower total network risk of 0.0366 and a maximum response time of 63 minutes.

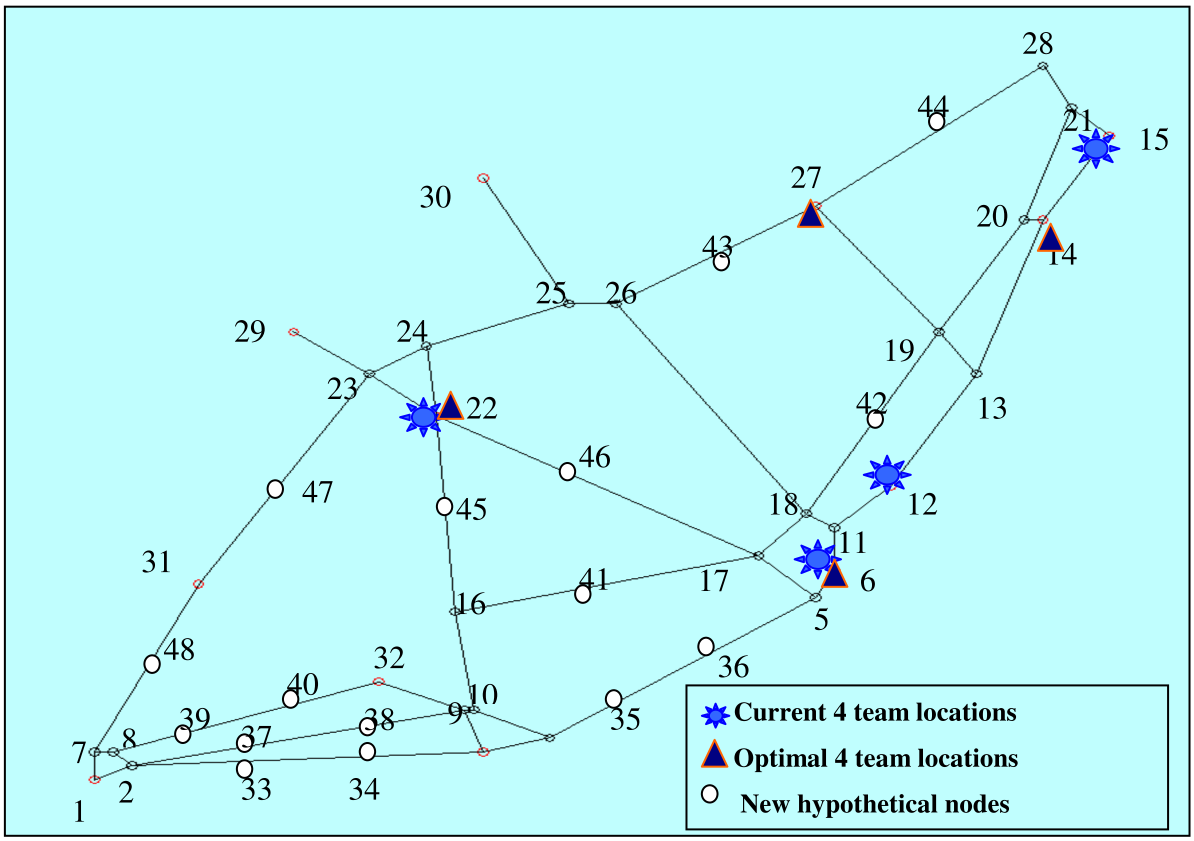


Figure 6-12: Location solution for a less aggregated network with 48 nodes (network 3)

To further investigate the effect of level of aggregation on location solution, more hypothetical nodes on long links were added to refine the initial network as shown in Figure 6-12. Using the less aggregated network with 48 nodes resulted in the same optimal solution as the initial network of 32 nodes with slightly higher estimates of total network risk than network 1.

Table 6-13: Comparison of risk and location results using different levels of aggregation

	HazMat teams optimal locations				Tot risk (fatality/yr)	Max Risk (fatality/yr)	Max response time (min)
Current solution	6	12	15	22	0.0390	0.0063	62
Optimal solution for network 1*	6	14	22	27	0.0372	0.0067	50
Risk minimizing solution for network 2**	12	15	27	29	0.0366	0.0050	63
Optimal solution for network 2**	6	15	27	29	0.0371	0.0050	58
Optimal solution for network 3***	6	14	22	27	0.0379	0.0037	63

*Network 1: initial network representation with 32 nodes
**Network 2: adding one hypothetical node on the longest link
***Network 3: less aggregated network with 48 nodes

It should be noted that a suitable level of aggregation differs for different problems depending on the network characteristics, available data, as well as the spatial scope of the analysis. For the application of the model, investigating different levels of aggregation using the problem in hand is recommended in order to assess the impact the aggregation level might have on the HazMat team location decision.

6.3 Input Parameters

Sensitivity analysis show that while variation in some input parameter might have a great effect on risk estimates and the choice of the optimal solution; other parameters have no or little effect on the model performance. Input values that highly affect the model performance are:

HazMat volumes and routs: HazMat traffic data is not readily available and rather usually obtained as aggregated values or only on origin-destination bases. The model proved to be sensitive to the routes and volumes of HazMat in the region. If possible, extra measures should be taken to best estimate the needed HazMat traffic data in the region.

Accident and release frequencies: the developed model can estimate different release frequencies for different highway and link types depending on different accident outcome probabilities. However, lack of such specific accident outcomes data for the considered case study area prevented the illustration of the model full features in this area. A detailed link-specific accident and release data that is dependant on the link characteristics would enhance the model performance.

Weather conditions: it is anticipated that considering a distribution of weather conditions at different nodes would improve the model performance.

Assumed time elements: assumed values for the maximum release duration, the maximum acceptable response time, the dispatch and the mitigation times affects the choice of the optimal solution. Better realistic estimates of such values will help enhance the model performance.

It was found that uniform input parameter values are of low significance on location decisions. Using uniform values for all links of parameters such as accident rates, traffic volumes, and weather conditions could introduce error to the risk estimate and the HazMat teams' optimal location solution. It was also found that level of node aggregation will have an effect on the risk and location results; however it should be assessed on case-by-case bases.

6.4 Summary

This Chapter introduced a case study to illustrate the risk-based HazMat team location optimization model features. Different model input parameters were introduced and a sensitivity analysis was carried out to examine how sensitive the developed model is to the change in different input parameters. As expected, risk estimates were found to differ for different input parameters. Change in certain parameters uniformly for the whole network, in most cases, results in a linear change in risk estimates; however these changes do not affect the choice of optimal solution. In contrast, parameters that have different change patterns for different parts of the network (e.g. different HazMat routes and different HazMat volumes for different links), will likely affect the choice of the optimal solution.

CHAPTER 7: MODEL APPLICATION

This chapter will use the case study of the southwestern Ontario region (shown in Figure 6-1) as an example to illustrate the features and potential applications of the developed model. A number of issues will be investigated including,

1. Assessing Risk Implication of the Current and the Optimal HazMat Team Location Solutions.
2. Regionally Planning HazMat Emergency Response to Determine Suitable Number and Locations of HazMat Teams.
3. Examining the Effectiveness of the Current System as Compared to a System Comprising of Fewer HazMat Teams.
4. Investigating Effect of Locating HazMat Teams to Any Node on the Network.
5. Assessing the Effect of Different HazMat Routing Strategies on HazMat Emergency Response Planning.
6. Investigating Emergency Response Requirements for Different HazMat Types.
7. Investigating Environmental Impact.

7.1 Assessing Risk Implication of the Current and the Optimal HazMat Team Location Solutions

This section illustrates the use of the HazMat team location model in assessing the risk implication of the current locations of four HazMat teams within the study region. The HazMat team location model then compares the risk implication of the current solution to the optimal solution for locating the same four teams so as to minimize total network risk subject to a maximum response time threshold of 60 minutes to any node on the network.

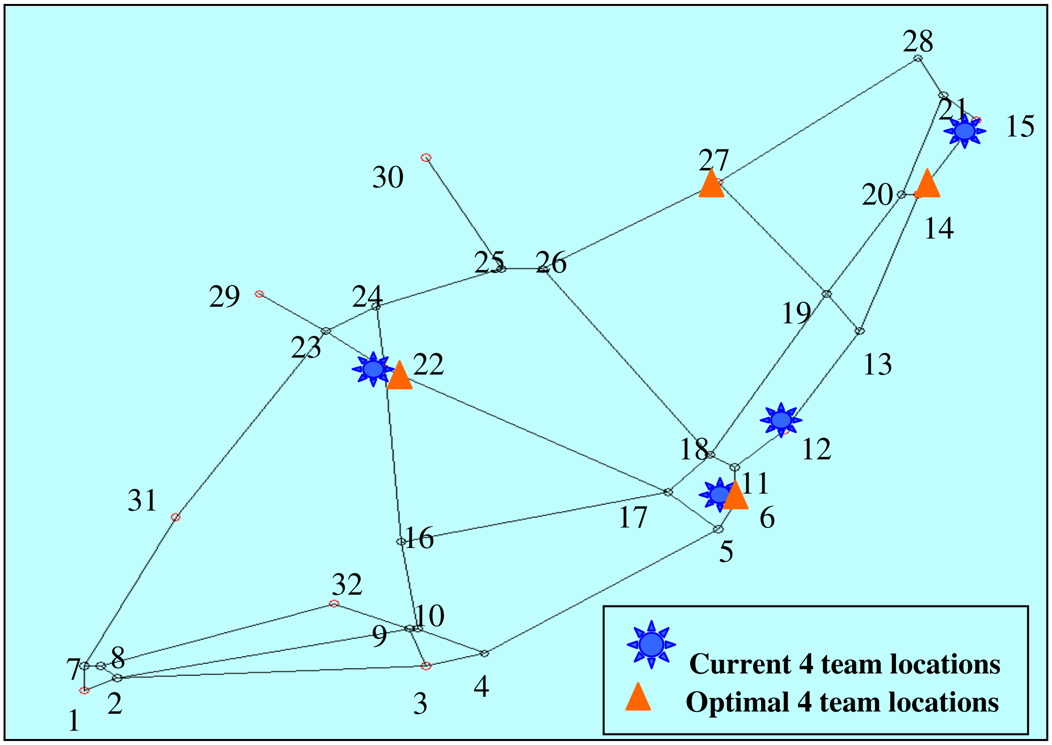


Figure 7-1: Current and optimal locations for four HazMat teams

Currently there are four HazMat teams located at nodes 6, 12, 15 and 22 (Figure 7-1) with a total region risk of 0.0412 fatalities/year and a maximum response time of 50 minutes. Figure 7-2 shows that flammable liquids contribute the greatest to the total network risk (60%). Toxic gases are the second greatest offenders, with a 34% contribution to total network risk, while flammable gases contribute only 6% to total network risk. The high percentage of flammable liquids risk is due to its large volume of movement on the network (64% of all HazMat). Although movements of volumes of toxic liquefied gases are small, they still have a substantial impact on total network risk because of their great consequent effect.

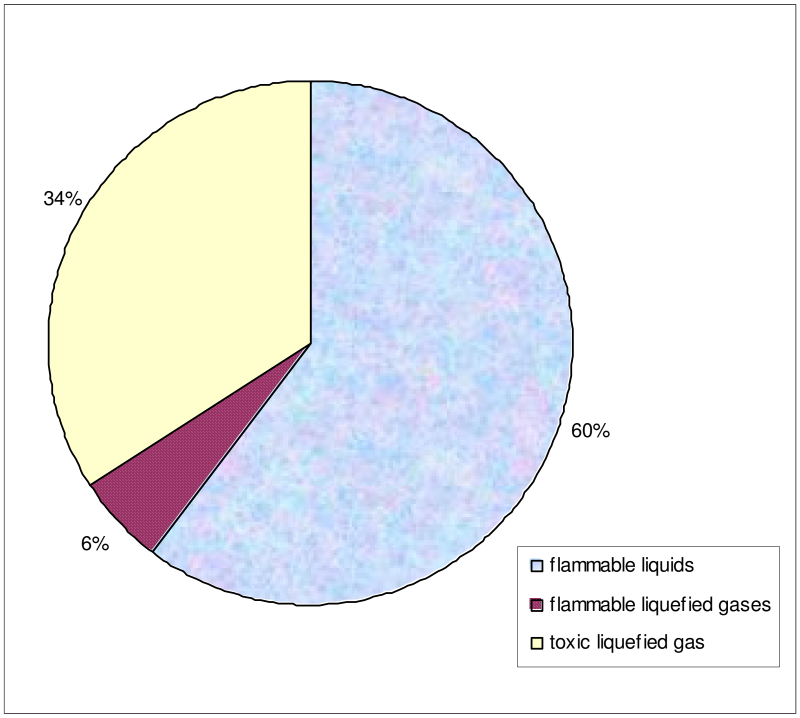


Figure 7-2: Different HazMat types contribution to total risk on the network

Optimally locating four teams, the solution resulting in the minimum total network risk while ensuring that response time to any node on the network does not exceed 60 minutes would be at node 6, 14, 22 and 27 as shown in Figure 7-1. The optimal solution would result in a total network risk of 0.0372 fatality/year, about 10% lower than the current solution. Table 7-1 summarizes the total network risk, maximum node risk, and maximum node response time estimates for the current and optimal solutions of all four HazMat teams. The four nodes suggested by the optimal solution differ from the current location (two nodes in common). Both location strategies have a maximum response time of 50 minutes.

Table 7-1: Risk and maximum response time results for current and optimal locations of 4 HazMat teams

	1st	2nd	3rd	4th	Total risk (fatality/yr)	Max risk (fatality/yr)	Max response time (min)	Reduction in Total risk (%)
Current locations	6	12	15	22	0.0412	0.0063	50	
Optimal locations	6	14	22	27	0.0372	0.0067	50	9.8%

Figure 7-3 illustrates the relationship between all possible location solutions and total network risk in an increasing order. The optimum solution, by definition, gives rise to the lowest network risk. About 10% of all possible solutions give lower total network risk than the current solution (i.e. node 6, 12, 15, 22).

For this case study, results fall within a fairly narrow band: the best location solution gives a reduction in total network risk of only 0.4 fatalities/100 years compared to the current solution, and only 2 fatalities/100 years less than the worst solution at nodes 1, 3, 30, and 32. However, as discussed earlier in Section 2.6, given the inherent uncertainties in the QRA analysis, the absolute values of the risk estimates are less significant than the relative values. Compared to the current solution, the optimal solution gives a reduction of 10 % in total network risk, and about a 34 % reduction in total network risk when compared to the worst solution.

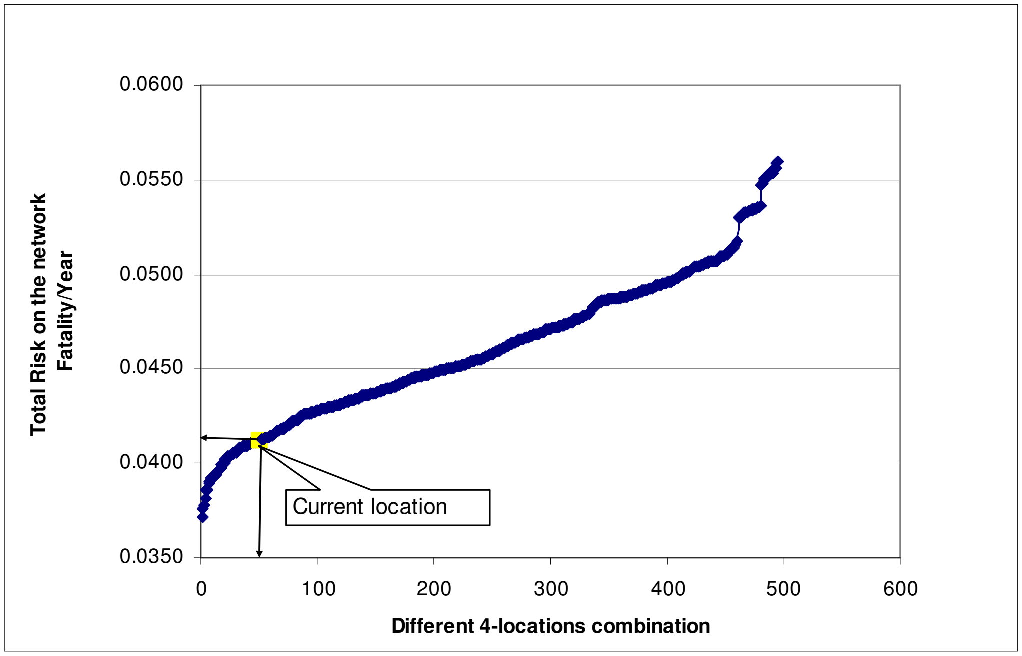


Figure 7-3: Relationship between locations and total risk in the region (based on exhaustive search)

7.2 Regionally Planning HazMat Emergency Response to Determine Suitable Number and Locations of HazMat Teams

This section details how the model can be used to regionally plan HazMat emergency response for transport related HazMat incidents. For the purposes of illustration, our case study region is assumed to lack any HazMat emergency coverage. As planners, we would like to find out the appropriate number and locations of HazMat teams needed to efficiently cover the considered region.

To find out the relationship between total network risk and number of HazMat teams, we ran the model for optimally locating only one HazMat team, to locating HazMat teams at all fire stations (total of 12). Figure 7-4 shows the relationship between total network risk and the number of HazMat teams on the network for optimal HazMat location solutions with a maximum response time threshold of 60 minutes. Under the 60 minutes maximum response time constraint, there is no feasible solution for locating one HazMat team.

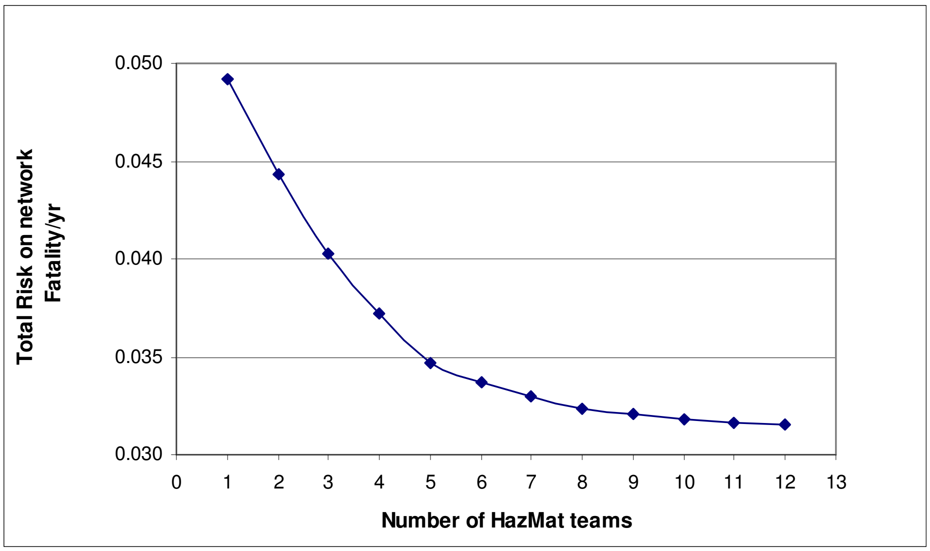


Figure 7-4: Relationship between total risk and number of HazMat teams on the road network with 60 minutes restriction on maximum allowable response time

As expected, increasing the numbers of HazMat teams results in a decrease of total network risk. The rate of reduction in network risk is highest for up to five HazMat teams, after which the relationship flattens out. Four to five teams would reflect the higher reduction rate in total network risk per additional team than for a higher number of teams. Thus, if the number of HazMat teams is a reflection of cost, we would suggest a number of four to five teams for this case study region. The following sections discuss the results of applying the proposed model to locating a given number of HazMat teams.

- **Locating one HazMat team**

Assuming one HazMat team is to be located, the best risk minimization location is Oakville (node 14) which results in the lowest total risk in the region of 0.0492 fatalities/year. However, this location solution does not satisfy the maximum response time restriction of 60 minutes for some marginal nodes. For example, the response time for Woodstock, node 7, is 94 minutes. Figure 7-5 shows the minimum total risk solution for one HazMat team notwithstanding the maximum response time constraint.

When we consider the maximum response time as the selection criterion, the best location is Hamilton (node 6, near the geometric center of the network). This choice results in a total network risk of 0.0547 fatalities/year. The maximum response time for this decision is 65 minutes for node 31 which is still unacceptable. Furthermore, for a one-team case, no solution exists that will yield a maximum response time less than 60 minutes, which means there is no feasible solution under the maximum response time constraint. Results show that the optimal solution, not withstanding maximum response time restriction, favors densely populated areas (node 14), while restricting maximum response time results in locations more toward the center of the considered region (node 22).

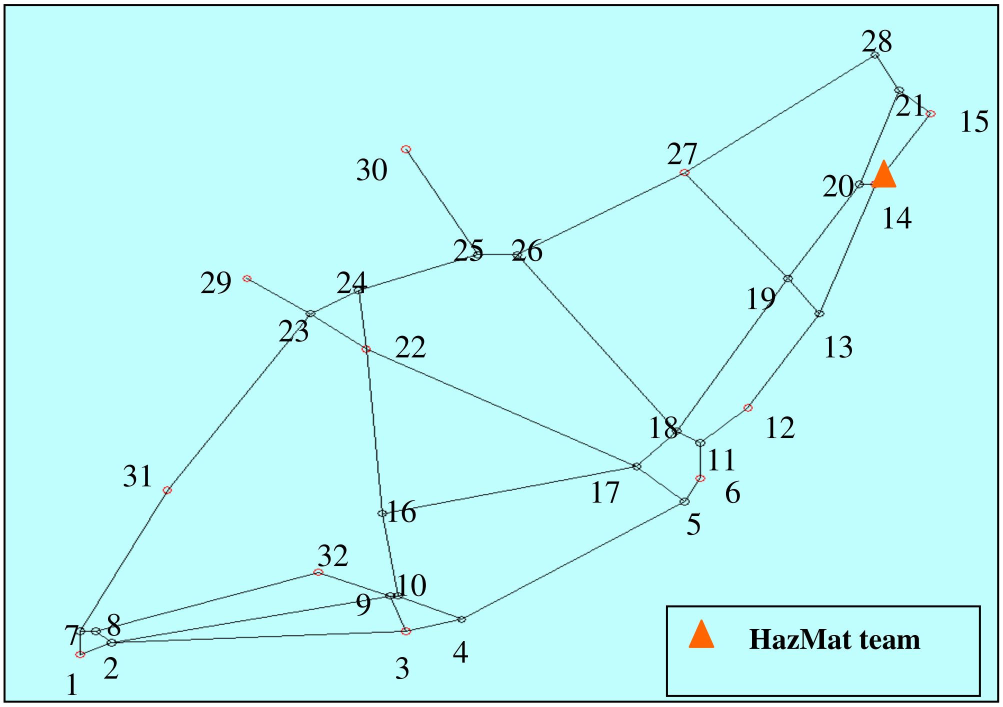


Figure 7-5: Minimum risk solution of locating one HazMat team

- **Locating two HazMat teams**

If two HazMat teams are available for allocation, the risk minimization solution is Hamilton (node 6) and Oakville (node 14) which yields a total network risk of 0.0444 fatalities/year and a maximum response time of 66 minutes. Given our maximum response time standard of 60 minutes, this solution is unacceptable; however, moving these two HazMat teams to other nodes can result in an acceptable two-team solution. For example, moving the HazMat team from Hamilton (node 6) to Cambridge (node 22), as shown in Figure 7-6, results in a total risk of 0.0458 fatalities/year, a10% increase from the risk minimization solution, and a maximum response time of 50 minutes. By considering all possible combinations for two-HazMat team solutions, we found that this solution yielded the lowest network risk subject to the 60 minutes maximum acceptable response time.

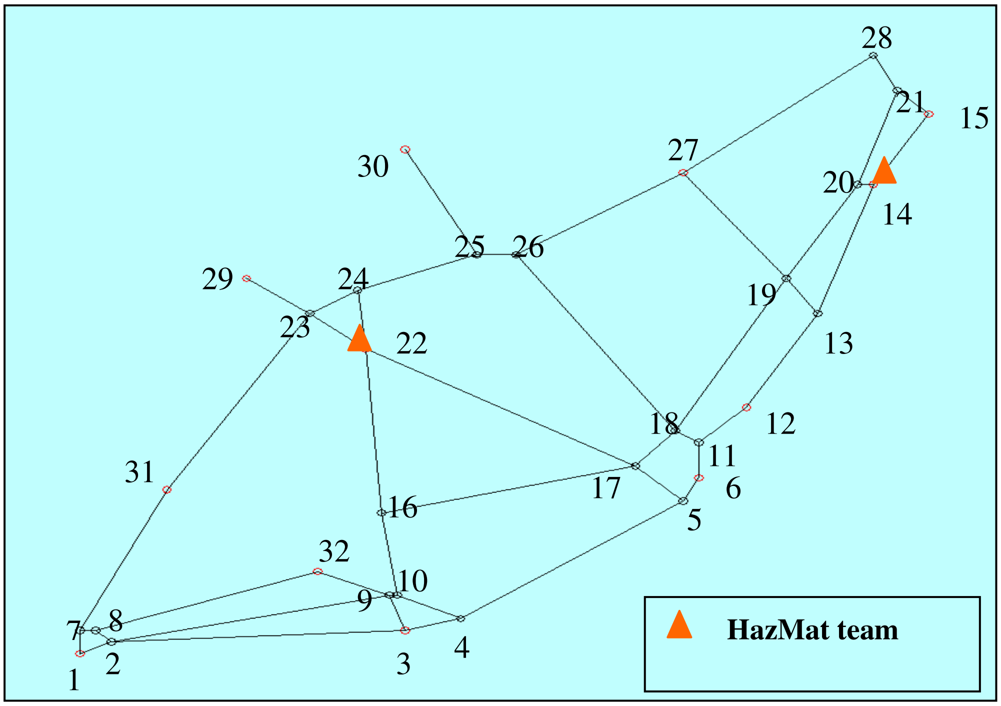


Figure 7-6: Two-team solution for minimum total risk subject to 60 min. maximum response time

Results confirm that for limited HazMat coverage, relaxing the maximum response time restriction favors locations at high populated areas (node 6 and 14), while imposing this restriction results in a solution which still services highly populated areas through node 14, while ensuring enough coverage for marginal nodes through node 22.

- **Locating three HazMat teams**

The risk minimization solution of three HazMat teams is at Oakville (node 14), Hamilton (node 6), and Milton (node 27). This solution yields the lowest network risk of 0.0403 fatalities/year. The maximum response time for this solution is still unacceptable at 64 minutes; however, again moving the HazMat team from Milton (node 27) to Cambridge (node 22), as shown in Figure 7-7, results in an acceptable maximum response time of 50 minutes. This solution is achieved, however, at a higher network risk of 0.0411 fatalities/year.

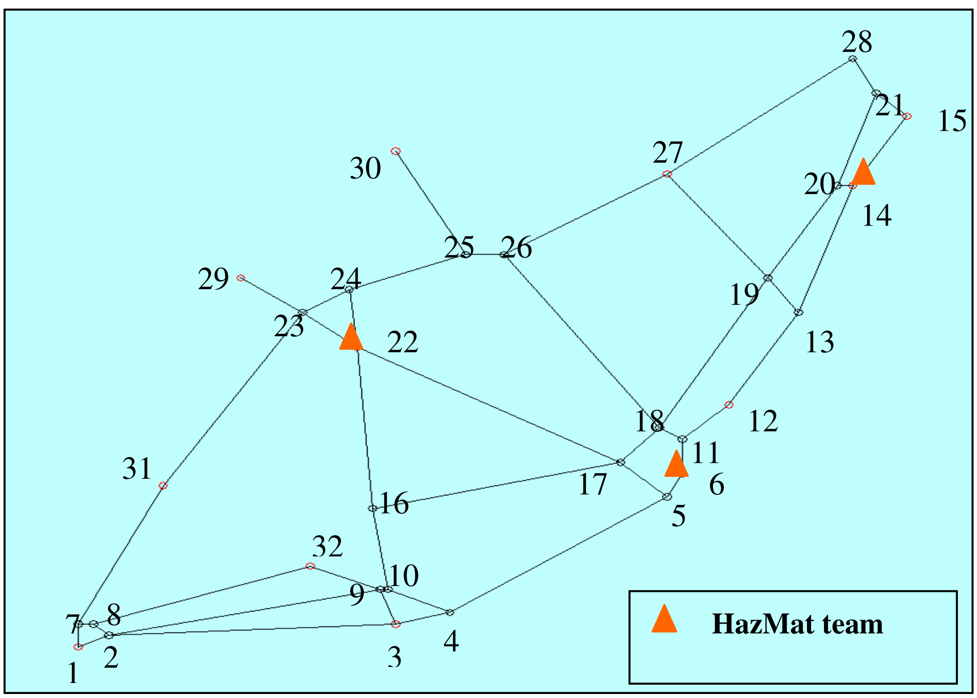


Figure 7-7: Three-team solution for minimum total risk subject to an acceptable maximum response time

- **Locating four HazMat teams**

When the total number of teams to be located is increased to four, the risk minimization solution is also a feasible solution under the maximum response time constraint. As shown in Figure 7-8, the optimal solution is to locate teams at Oakville, Hamilton, Milton, and Cambridge with a total network risk of 0.0372 fatalities/ year and a maximum response time of 50 minutes.

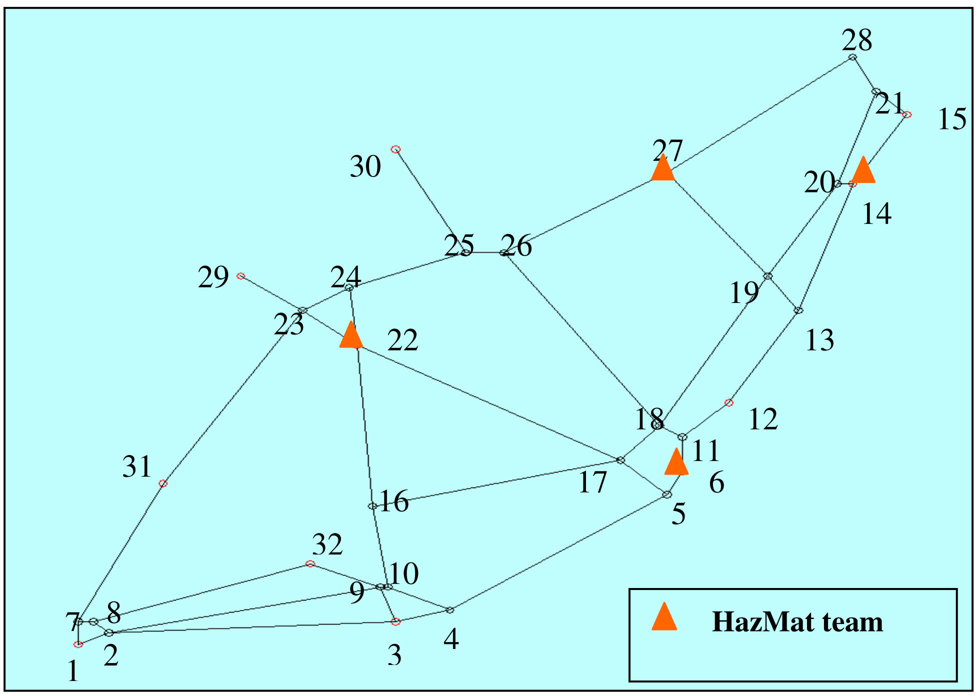


Figure 7-8: Current and optimal four HazMat teams solution

A comparison of the location solutions of one to four HazMat teams is given in Table 7-2. In this table we have included, for comparison purposes, the current four-team location solution of Mississauga (node 15), Burlington (node 12), Hamilton (node 6) and

Cambridge (node 22). The application of the model produces a four HazMat team solution that yielded a 10 % reduction in risk.

Table 7-2: Comparison of minimum total network risk solutions for 1, 2, 3, and 4 teams

Number of HazMat teams	Locations (nodes)				Tot risk (fatality/yr)	Max Risk (fatality/yr)	Max response time (min)
1				14	0.0492	0.0067	94
2			6	14	0.0444	0.0067	66
3		6	14	27	0.0403	0.0067	64
4	6	14	22	27	0.0372	0.0067	50
Current locations	6	12	15	22	0.0412	0.0063	50

Maximum response time for current locations is 50 minutes. Thus, if planners are willing to accept a maximum response time of 64 minutes, the number of HazMat teams could be reduced to three, keeping node 6, relocating 15 and 22 to 14 and 27, and closing the team at 12. The resultant total network risk is 0.0372 fatalities/year (lower than the current solution at 0.0403 fatalities/year).

7.3 Examining the Effectiveness of the Current System as Compared to a System Comprising of Fewer HazMat Teams

This section investigates the possibility of closing certain HazMat teams and how such a decision will affect the total risk estimate. Assuming a decision is made to reduce the current HazMat teams to three teams only, the question of which one to close arises.

We ran the model for four runs, each time removing one HazMat team and keeping the other three. Table 7-3 shows a comparison between the locations of the current four and the proposed three-team locations. Accordingly, best location to close was found to be node 6, a decision that would result in the lowest increase in total network risk of 3.2%. Baring in mind that node 6 represents the city of Hamilton and, over-and-above responding to transport related HazMat accidents on the road network, the HazMat team at Hamilton is responsible for responding to other non-transport related HazMat incidents within the city, closing the HazMat team at node 6 is somewhat impractical. Thus, the next choice is to close the team at node 12, Burlington, with an increase in total risk of 5.2 % from current value. In this case, given the population involved, we would probably recommend the closure of Burlington instead of Hamilton with the recommendation of further evaluation of the non-transport related HazMat incidents at Burlington. It should be noted, however, that closing of HazMat team at Mississauga (node 15) will result in the greatest increase in network risk of 15 %.

Table 7-3: Results for proposed closing of one of the existing HazMat teams

	HazMat teams location				Total risk (fatality/year)	Max risk (fatality/year)	Max response time (min)	Change in Total risk (%)
Current locations	6	12	15	22	0.0412	0.0063	50	
close 6		12	15	22	0.0425	0.0063	50	3.2
close 12		6	15	22	0.0433	0.0063	50	5.2
close 22		6	12	15	0.0444	0.0063	66	7.8
close 15		6	12	22	0.0473	0.0074	50	14.9

While deciding on a HazMat team closure, planners might be willing to relocate one of the remaining teams in order to maintain total network risk at its current level. Accordingly, we investigated all possible solutions of closing one team and re-locating another.

Table 7-4: Results for maintaining network risk subject to closing one team, relocating another

HazMat team locations				Total risk (fatality/year)	Max risk (fatality/year)	Max response time (min)	Change in Total risk (%)
6	12	15	22	0.0412	0.0063	50	Current locations
	12	15	27	0.0417	0.0058	73	1.2
	6	15	27	0.0424	0.0058	64	2.9
	12	15	22	0.0425	0.0063	50	3.2
	6	15	22	0.0433	0.0063	50	5.2
	6	12	14	0.0434	0.0067	66	5.3
	12	22	27	0.0440	0.0067	50	6.7
	15	22	27	0.0442	0.0058	50	7.2
	12	15	29	0.0444	0.0063	57	7.8
	6	12	15	0.0444	0.0063	66	7.8
	12	15	31	0.0446	0.0063	53	8.3
	6	22	27	0.0448	0.0067	50	8.7
	6	15	29	0.0452	0.0063	57	9.7
	12	15	32	0.0453	0.0063	63	9.8
	12	15	30	0.0453	0.0063	69	10.0
	6	15	31	0.0454	0.0063	48	10.2
	6	12	27	0.0458	0.0067	64	11.0
	6	15	32	0.0461	0.0063	62	11.7
	6	15	30	0.0461	0.0063	64	11.9
	6	12	22	0.0473	0.0074	50	14.9
	15	22	31	0.0476	0.0063	50	15.6
	15	22	32	0.0477	0.0063	46	15.8
	15	22	30	0.0479	0.0063	50	16.3
	15	22	29	0.0479	0.0063	50	16.3
	12	22	31	0.0481	0.0074	50	16.7
	12	22	32	0.0482	0.0074	47	16.9
	12	22	30	0.0484	0.0074	50	17.4
	12	22	29	0.0484	0.0074	50	17.4
	6	22	31	0.0490	0.0074	57	18.9
	6	22	32	0.0491	0.0074	57	19.2
	6	12	29	0.0492	0.0074	57	19.4
	6	22	30	0.0493	0.0074	54	19.6
	6	22	29	0.0493	0.0074	57	19.7
	6	12	31	0.0494	0.0074	48	19.9
	6	12	32	0.0501	0.0074	62	21.5
	6	12	30	0.0501	0.0074	64	21.6

Results in Table 7-4 show that the closest solution to the current level of total network risk would be keeping the teams at node 12 and 15, closing the team at 6, and relocating 22 to 27. The proposed solution will result in an increase of 1.2 % in total network risk, correspondent to a total risk of 0.0417 fatalities /year; however the maximum response time of this solution is 73 minutes.

The best alternative that satisfies the 60 minutes maximum response time threshold would be to close the HazMat team at node 6 (Hamilton) without the need to relocate any other team. This solution results in a 3.1 % increase in the total network risk and a maximum response time of 50 minutes. Considering the desirability of maintaining the HazMat team at node 6, the next alternative is to close the HazMat team at node 12 without the need to relocate any other teams. This solution gives an increase of 5.2% in total network risk

7.4 Investigating Effect of Locating HazMat Teams to Any Node on the Network

HazMat teams are usually allocated to existing fire stations to keep initial and operating costs at reasonable limits. Restricting HazMat teams to existing fire stations results in location patterns similar to those of fire stations, i.e. locations are mainly associated with large populated areas. However, such a restriction not only limits the ability to obtain solutions that may further minimize risk, but also might result in improbable solutions under the maximum response time constraint, especially for remote areas.

This potential problem is investigated in this section as well as how the relaxation of this location restriction might affect HazMat risks and team locations in the region.

Although this may not be a practical solution due to financial aspects, understanding what the implications would be in case such a restriction is lifted would be helpful.

We ran the model to locate four HazMat teams at any node on the network with no limitation on the host node (i.e. with or without fire stations). The optimal solution results, along with results from Section 7.1 for the current and optimal four-team solution with the restriction of HazMat teams to fire stations, are shown in Table 7-5. Locations of the optimal solutions for both restricted and unrestricted cases are shown in Figure 7-9. As shown, the unrestricted optimal HazMat team locations solution actually favors two nodes with existing fire stations, node 12 and 27.

Table 7-5: Comparison of four HazMat team location strategies

Strategy	Locations (nodes)				Tot risk (fatality/yr)	Max Risk (fatality/yr)	Max response time (min)	% Reduction in total network risk
Current	6	12	15	22	0.0412	0.0063	50	
Restricted to fire stations	6	14	22	27	0.0372	0.0067	50	9.8
No restriction	12	21	23	27	0.0354	0.0043	56	14.2

For the considered case study, the optimal solution of either the restricted or unrestricted location strategies yields a reduction in total network risk. As expected, the lowest risk is associated with the unrestricted location of HazMat teams, with a reduction in total network risk of 14.2% as compared to the current location solution, and a reduction of 4.4% as compared to the fire station restricted solution. The unrestricted strategy appears to be especially desirable with respect to the maximum risk measures since it results in much lower values of maximum risks at the marginal nodes.

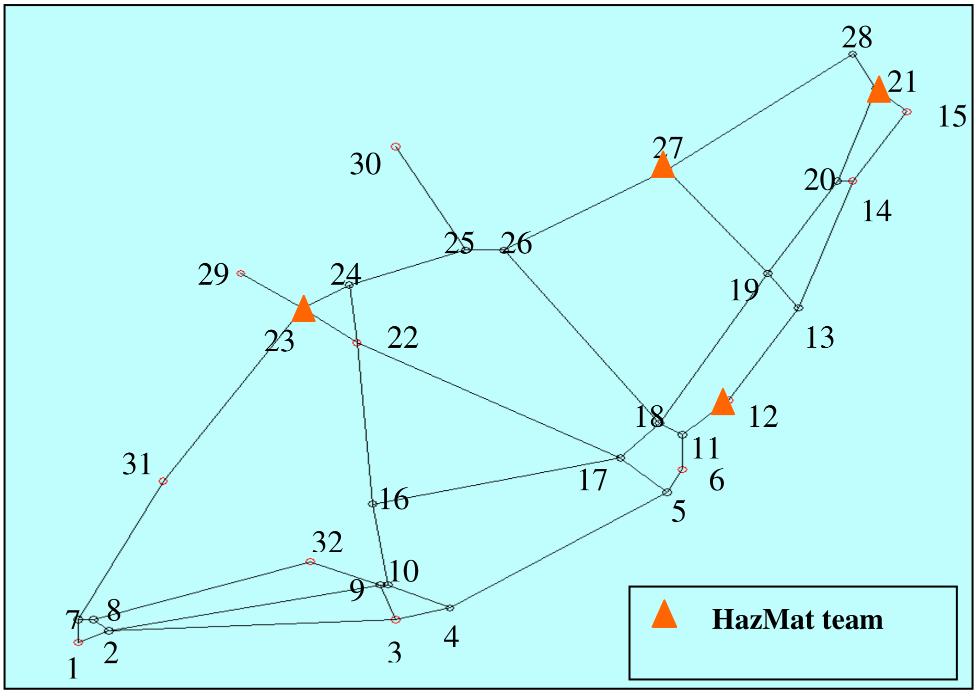


Figure 7-9: Optimal solutions of 4 HazMat teams for both fire station restricted and unrestricted locations.

Not withstanding the fact that the unrestricted strategy yields the lowest risk, practical issues exist as to whether placing HazMat teams at locations that do not have fire stations is possible. Based on this consideration, we would recommend adapting a restricted four HazMat team location strategy for this region.

7.5 Assessing the Effect of Different HazMat Routing Strategies on HazMat Emergency Response Planning

The developed model was used to estimate the risk implications of two routing strategies. Under the first routing strategy, HazMat are to be transported on all links in proportion to the truck movements. The second strategy is to route all HazMats movements on the 401, a main transport corridor, and the QEW (and part of 403 between Mississauga and Hamilton) which carries most of the shipments from eastern Canada across the USA border at Niagara Falls.

Table 7-6 lists the risk results of the two assumed strategies for the current HazMat team locations. Results show that the second strategy of routing all HazMat movements on the two main corridors in the region (and subsequently through highly populated areas) results in a slightly higher total network risk than the first routing strategy.

Table 7-6: Risk results for the two different routing strategies for the current HazMat team locations

Strategy	Tot risk (fatality/yr)	Max Risk (fatality/yr)	Max response time (min)
Strategy 1*	0.0412	0.0063	50
Strategy 2**	0.0416	0.0094	50

*Strategy 1: routing HazMat movements to all links
**Strategy 2: routing HazMat movements to 401, 403, and QEW highways

Furthermore, optimal HazMat team location solutions were compared for the two different routing strategies (

Table 6-12). The results show that the effect of different routing strategies on the total network risk estimate is relatively small. However the location of the optimal solution differs for the two routing policies, as shown in Figure 7-10. Thus, if all HazMat movements are routed through 401 and QEW, Burlington (node 12) and Mississauga (node 15) become more favorable than Hamilton (node 6) and Oakville (node 14).

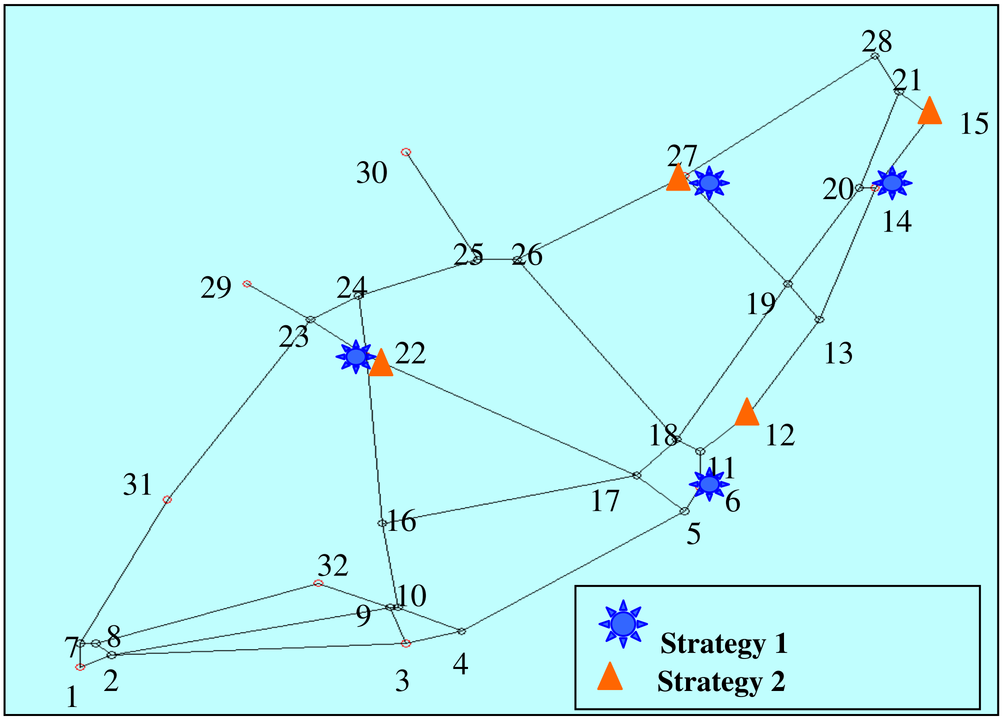


Figure 7-10: Four locations solutions for two different routing policies

Table 7-7: Four HazMat teams optimal locations for the 2 different routing strategies

					Tot risk (fatality/yr)	Max Risk (fatality/yr)	Max response time (min)
Strategy 1	6	14	22	27	0.0372	0.0067	50
Strategy 2	12	15	22	27	0.0365	0.0088	50

7.6 Investigating Emergency Response Requirements for Different HazMat Types

Release of different HazMat types requires different response and mitigation measures. Each HazMat type requires different training levels, body protection, and containment and decontamination equipment. For example, body protection equipments for chemical hazards differ significantly from those for thermal hazards.

This section investigates whether or not optimal HazMat team locations differ for different HazMat types. Each type of HazMat was considered individually when searching for the optimal HazMat team locations that would minimize total network risk for that type of HazMat. We anticipated that different HazMat type would require different HazMat team locations; however Table 7-8 shows that for this case study, optimal solutions are the same for all types of HazMat as well as for all HazMat types combined.

Table 7-8: Optimal HazMat teams location for different types of HazMat

HazMat type	Optimal locations				Tot risk (fatality/yr)	Max Risk (fatality/yr)	Max response time (min)
Flammable liquid	6	14	22	27	0.0220	0.0041	50
Flammable liquefied gas	6	14	22	27	0.0020	0.0004	50
Toxic liquefied gas	6	14	22	27	0.0132	0.0021	50

7.7 Investigating Environmental Impact of HazMat Releases

In this section we investigate the environmental impact of HazMat releases as discussed in Section 5.4. The impact of the HazMat release on the environment is assumed to be linearly related to the amount released. Furthermore, an environmental impact index was used as an environmental risk measure. This index is meant to represent impact on existing vegetation and wild life, long-term effects, as well as clean-up and rehabilitation costs. Different weights were assumed for different HazMat types depending on their perceived impact as shown in Table 7-9.

Table 7-9: Environmental risk impact weights for different types of HazMat

HazMat type	Weight of environmental impact
Flammable gases	1
Toxic gases	5
Flammable liquids	10
Toxic liquids	100

Table 7-10 shows the environmental risk and location results for the current and optimal solutions. Consequently, the current solution was found to result in an environmental risk index of about 363, while the optimal solution was 50 points less (about 15 %) than the current HazMat team solution.

Table 7-10: Environmental risk and location results for the current and optimal location

	HazMat team locations				Total risk	Maximum risk	Max response time (min)
Current	6	12	15	22	364	44	50
Optimal	6	14	27	31	317	25	48

The optimal solution for environmental impact favors locations at Hamilton, Oakville, Milton, and Parkheaven—placements that differ significantly from current HazMat team locations. Figure 7-11 shows the optimal locations of the four HazMat teams in order to minimize total network environmental impact.

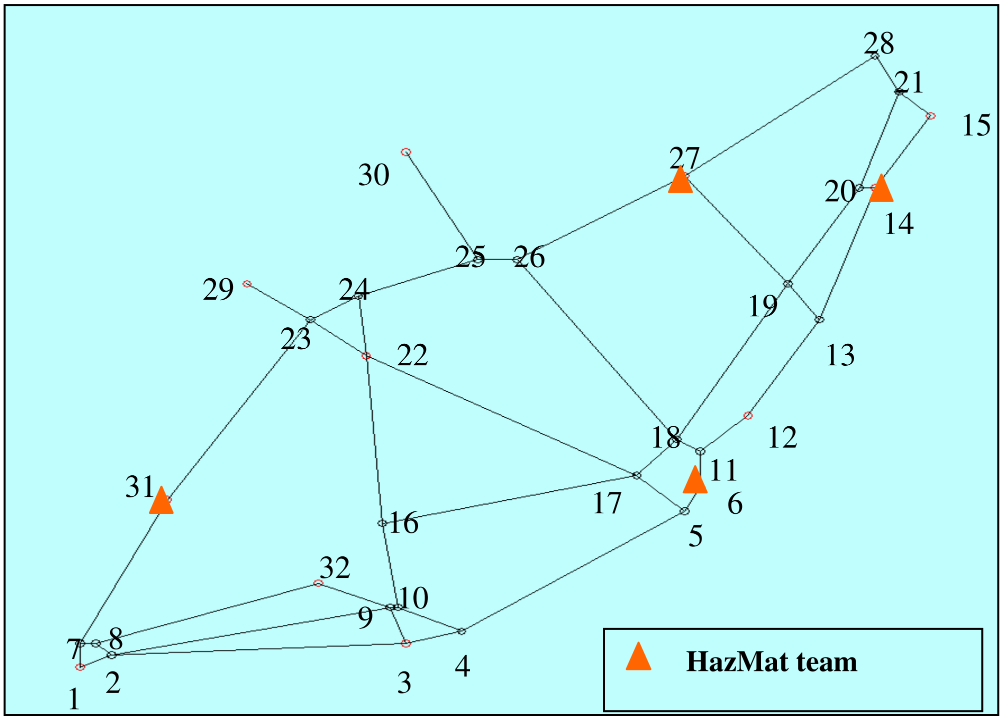


Figure 7-11: Optimal locations of four HazMat teams to minimize total network environmental impact

Figure 7-12 shows the relationship between different HazMat team location solutions and the total environmental impact in the region. From Figure 7-12 we can clearly see that, in terms of environmental impact, numerous better solutions exist in comparison to current HazMat team locations. Figure 7-13 shows the relationship between environmental impact and the number of HazMat teams, illustrating that the total impact decreases with increase in the number of HazMat teams. Finally, the rate of reduction in total risks is higher for fewer HazMat teams than for larger numbers of HazMat teams.

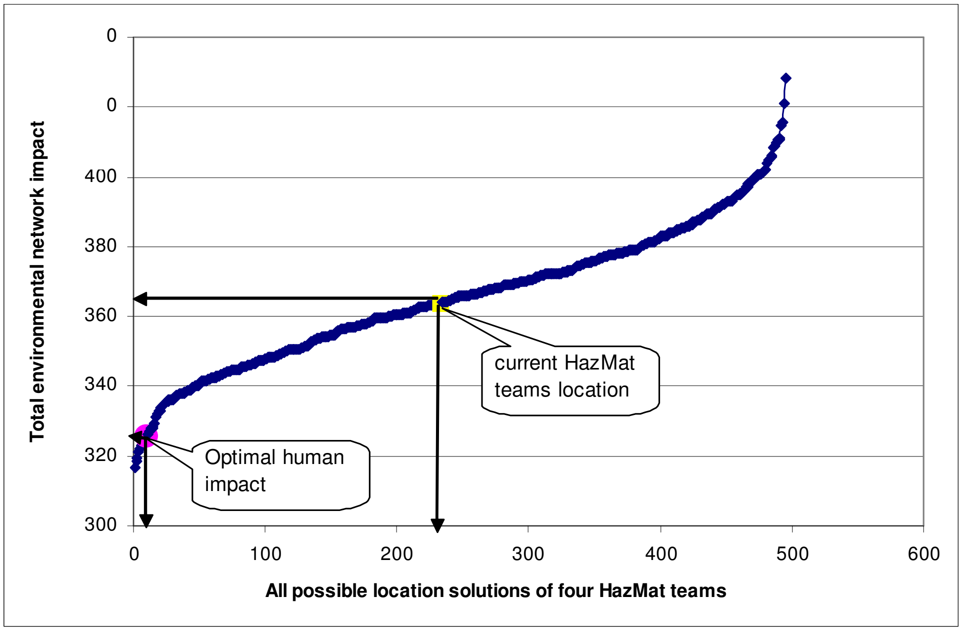


Figure 7-12: Relationship between locations and environmental total impact in the region

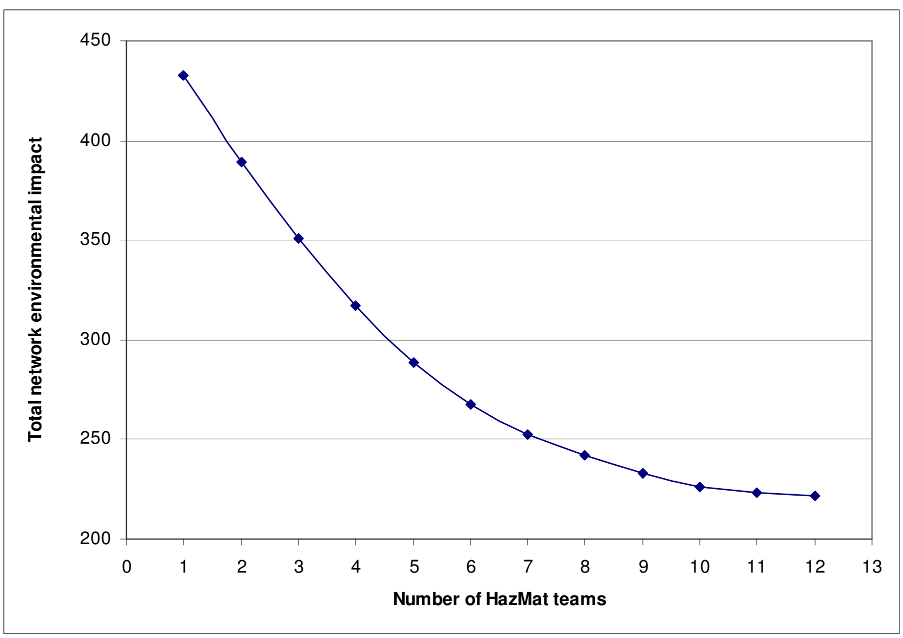


Figure 7-13: Relationship between number of HazMat teams and total environmental impact on the network

7.8 Summary

This case study is aimed mainly at illustrating features and capabilities of the developed HazMat team locations model. Consequently, the model has demonstrated some useful features in addressing the following questions: What are the risk implications of the current HazMat team locations? How many HazMat teams shall be located in a region? Where should they be located? Would it be beneficial to close or relocate some teams? What are the impacts of different routing strategies? And, what is the environmental impact of HazMat releases?

CHAPTER 8: CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

The transportation of HazMat poses special risks for the neighboring population and environment. Recent analyses as well as historical events have shown that risks arising from the transportation of HazMat are often of the same magnitude as those resulting from fixed facilities. Fortunately, providing efficient emergency response throughout the road network can substantially reduce HazMat transport risks. However, a systematic approach has yet to be developed to determine where regional HazMat teams should be placed. Currently, planning HazMat emergency response is carried out at the local level with no standardized method for the planning process.

8.1 Conclusions

This thesis introduces a risk-based HazMat team location optimization model to provide decision-making support for locating emergency response facilities, specifically to response to HazMat transport accidents on the road network. The model provides a more objective set of input alternatives into the multi-criteria decision making process of regionally locating HazMat teams. The developed model consists of two components: 1) a Time-Dependant Quantitative Risk Assessment (TDQRA) module that estimates the risks for the network and at its specific nodes based on response time to each node, and 2) a location optimization module for locating HazMat teams on the network based on the risk involved. The model seeks to minimize total network societal risk associated with the transport of a representative number of HazMat while ensuring a minimum level of service (maximum allowed response time) at marginal areas.

This approach provides a practical platform for evaluating the trade-off between system costs (in terms of the number of teams located), total network risk, and risk and response time thresholds at individual nodes. The model was applied to an example network representing the southwestern Ontario region to illustrate its major features and capabilities.

The model makes use of a comprehensive time-dependant quantitative risk assessment technique that includes probabilities of accidents, accident induced releases for different release scenarios, emergency response time, corresponding hazard areas, and impacts on population (immediate health impacts). The TDQRA provides an effective comprehensive risk basis for deciding HazMat team locations. The model is time dependant in that risk consequence is dependant on the time it takes a HazMat team to respond to a HazMat release from the nearest location.

In order to solve the problem practically, a number of representative HazMat types and release scenarios were considered. The following four HazMat types were used: toxic liquefied gases (represented by Ammonia), flammable liquefied gases (represented by Propane), flammable liquids (represented by Gasoline), and toxic/corrosive liquids. Accordingly, four release scenarios were considered, namely large spill, small spill, large leak, and small leak. The adopted release scenarios are meant to reflect common release mechanisms associated with HazMat accidents. The TDQRA analysis considers only immediate health impacts for off-road population, and does not account for the possibility of evacuation or shelter. A preliminary investigation of the HazMat releases environmental impact was considered.

The location module involves locating a given number of HazMat teams at a set of pre-defined candidate locations to meet the demand for emergency service resulting from HazMat accidents at different network nodes. We assumed that the demand for HazMat emergency response took place at nodes of a link-node transportation network. Moreover, the problem is relatively small and was solved using complete enumeration since candidate locations are limited to a pre-defined set of nodes. Nevertheless, the location module in this research accommodates a genetic algorithm that could be used to find near-optimal solutions for larger problems.

The relevance of the application of the model was demonstrated through a case study of a southwestern Ontario regional highway network. The network consisted of 32 node and 92 links. In addition, a subset of 12 nodes currently host fire stations and are assumed to be the candidate nodes for HazMat team locations.

Uniform change in certain model parameters for the whole network, in most cases, resulted in a linear change in risk estimates, but not the choice of optimal solution. On the other hand, input values that have different change patterns for different parts of the network, e.g. different HazMat routes and different HazMat volumes for different links, will likely affect the choice of optimal solution.

To demonstrate the practical relevance of the model, a number of strategic HazMat location policies were investigated for the southwestern Ontario case study. Currently there are four teams in the region, with the current locations of these teams based on engineering judgment and not as a result of a comprehensive risk minimization procedure. In this thesis, the following practical issues were investigated:

1. Assessing risk implication of the current and the optimal HazMat team location solutions.
2. Regionally planning HazMat emergency response to determine suitable numbers and locations of HazMat teams.
3. Examining the effectiveness of this system as compared to a system comprising of fewer HazMat teams.
4. Investigating the effect of locating HazMat teams to any node on the network.
5. Assessing the effect of different HazMat routing strategies on HazMat emergency response planning.
6. Investigating emergency response requirements for different HazMat types.
7. Investigating the environmental impact of HazMat releases.

The model has demonstrated some useful features in resolving questions concerning different HazMat team location policies for the southwestern Ontario region.

The results of this exercise suggested that flammable liquids have the largest contribution to the total network risk (60%), while toxic gases place second with 34% contribution to total network risk. Lastly, flammable gases contribute only 6% to total network risk. The high percentage of flammable liquids risk is consistent with its large volume of movement on the network (64% of all HazMat). Although volumes of toxic liquefied gases are small, they still have a substantial impact on total network risk because of their great consequent effect.

The current number and location of HazMat teams are among the positive alternatives based on the risk minimization criterion. The current HazMat team location solution is only 10% away from the minimum total network risk solution, while the estimated annual total network risk of 0.04 fatalities appears to be consistent with the reported national average of 2 fatalities/year caused by HazMat transport accidents between 1997 and 2001 (Transport Canada 2002). Total risk on the network, however, would improve with re-location of some of the existing teams, but the reduction in total risk (10 %) may not be enough to overcome the costs of relocation.

The analysis has suggested that for the southwestern Ontario region, four or five HazMat teams provide the highest reduction in risk for an incremental increase in the number of HazMat teams. Moreover, results show a tradeoff between the number of HazMat teams, total risk, and maximum risk. Thus, the current use of four HazMat teams in the region is consistent with our findings.

Results also show that for a limited number of HazMat teams, the risk minimization solution, not withstanding maximum response time restriction, favors densely populated areas, while restricting maximum response time results in locations more toward the geographical center of the region. However, with enough coverage, in terms of the number of HazMat teams, the model demonstrated the ability to assess the risk contribution from different nodes and to choose the best solution based on risk optimization.

Current HazMat team locations unfortunately result in a high environmental impact of HazMat releases. Thus, increasing the number of HazMat teams to six and relocating them to different locations will dramatically decrease the environmental impact of HazMat releases.

Lastly, it should be noted that the findings of this case study are limited to the considered region only. However, while these findings are not suitable for deducing any general conclusions, the proposed methodology and the developed mode could be applied to any other geographical areas.

8.2 Recommendations and Future Work

The following items represent suggested areas of improvement that would enhance the performance of the developed TDQRA and HazMat team location model.

a) Enhancement to the developed TDQRA

- **Using link-specific HazMat accident and release rates.** HazMat accident rates and release probabilities depend on a number of features, such as road type and conditions, posted speed, topographical and environmental condition. However, estimates of HazMat accident rates and release probabilities are normally based on characteristics of broad classification or road type (e.g. urban verse rural). Thus, utilizing other factors, such as number of lanes, posted speed, and probability of overturn/collision, is recommended in estimating link-specific accident and release probabilities. Such link-specific estimates would enhance the choice of HazMat team locations.
- **Incorporating gas dispersion modeling directly into the TDQRA:** In developing the TDQRA, we used results from the gas dispersion model ALOHA to calculate concentration levels and doses for releases of different HazMat. Incorporating a gas dispersion modeling into the TDQRA will allow the consideration of a wider range of discharge rates, release times, and weather conditions.
- **Improving modeling of exposed population**. Expanding the developed TDQRA to consider HazMat risk imposed on the on-road population (road users) is recommended as well as taking into account shelter and evacuation as mitigation procedures. Moreover, examining the use of a population distribution instead of average population density for off-road population modeling is also recommended since improving modeling of the exposed population would contribute to a more realistic risk measure.

- **Considering uncertainty in input estimates.** Uncertainty in the risk assessment process arises from two aspects: the imprecision in estimating input parameters due to insufficient data, and the uncertainty in the HazMat release process itself due to system variations over time and space. Thus, we recommend that future research account for uncertainty in the TDQRA through the use of probability distributions for input parameters, such as accident and release rates, instead of single value estimates.
- **Enhancing Environmental risk assessment**. The developed environmental impact index could be improved by considering different relevant parameters, such as proximity to water bodies, ground water, conservation areas and other ecologically sensitive areas.

b) Enhancements for the developed location optimization module

- **Using Geographical Information System (GIS) to integrate spatial information into the developed model**. Preparing spatial data in a format compatible to the developed model could be time consuming and might result in errors. In contrast, integrating spatial data into the model would help manipulate data, save time, and help reduce the occurrence of errors.
- **Considering the hieratical aspect of HazMat emergency response.** Emergency response services, including HazMat response, are hierarchal in nature. Not all HazMat teams have the same level of response capabilities: a lower level team with less response capabilities is usually available for quicker response than a

higher level team. Thus, considering interaction among different levels of response would enhance the performance of HazMat emergency planning.

- **Model monetary costs of establishing new HazMat teams or relocating existing ones**. So far HazMat team costs have been expressed in terms of the number of teams. As a result, a more accurate representation of team costs that reflects the specialization of team members and equipment should be considered.

REFERENCES

Abuja, R. K., Magnanti, T. L., Orlin, J. B. 1993. *Network Flows: Theory, Logarithms and Applications*. Englewood Cliffs, Prentice Hall.

Aini, M.S., Fakhru'l-Razi, A, Daud, M., Ibrahim, W.M.N., and Tangavelu, S.K. 2001. Study on Emergency Response Preparedness of Hazardous Materials Transportation. *Disaster Prevention and Management: An International Journal*. v 10, n 3, p 183-188. Emerald Group Publishing Limited.

Anderson, J. H., Jr. 1991. *Testimony before the U.S. House of Representatives, Subcommittee on Government Activities and Transportation Committee on Government Operations*. Abstract. Available from: <http://www.ironwoodtech.com/library/abstracts/RA430002.htm>. Accessed May 2004.

Ang, A., Briscoe, J. 1989. *Development of a Systems Risk Methodology for Single and Multimodal Transportation Systems*. Final Report, Office of University Research, US Department of Transportation, Washington, DC.

Arendt, J. S., Lorenzo, D. K., and Lusby, A. F. 1989. *Evaluating Process Safety in the Chemical Industry – A Manager's Guide to Quantitative Risk Assessment*. Chemical Manufacturers Association. Washington, D.C.

Aytug, H., Saydam, C. 2002.Solving large-scale maximum expected covering location problems by genetic algorithms: a comparative study. *European Journal of Operational Research*. v 143, n 3, p 480-494.

References

Badri, M. A., Mortagy, A. K., Alsayed, C. A. 1998. Multi-objective module for locating fire stations. *European Journal of Operational Research*. v 110, n 2, p 243-260 Elsevier.

Batta, R., Mannur, N. 1990. Covering-location modules for emergency situations that require multiple response units. *Management Science*. v 36 p 16-23.

Berman, O., Chiu, S., Larson, R., Odoni, A., and Batta, R. 1990. Location of mobile units in a stochastic environment. In Mirchandani, P. and Francis, R. (Eds) *Discrete Location Theory*. John Wiley and Sons, New York, NY

Britter R.T., Griffiths R. F. 1982. *Dense Gas Dispersion*. Elsvier.

Brock University Map Library. 1999. 1996 Southern Ontario Census Maps, Population Density. Map. Brock University Map Library St. Catharines, ON. Available from. <http://www.brocku.ca/maplibrary/atlas96/s_ontario/SontPopDens.pdf>. Accessed May 2004.

Brown, D.F., Dunn, W.E., and Policastro, A.J. 2001. *A national risk assessment for selected hazardous materials transportation*. For the US Department of Energy. Available from: <www.osti.gov/dublincore/gpo/servlets/purl/776739-dpNd91/native/> Accessed May, 2004.

Button, N. 1999. *Release and Fire Incident Rates for Trucks Carrying Dangerous Goods.* Ph.D. thesis, University of Waterloo.

Canadian Council of Motor Transport Administrators coordinates. 1997. *1995 National Roadside Study (NRS)*, Truck Traffic Estimate Software Package (TTESP).

References

Canadian Council of Motor Transport Administrators coordinates. 2002. *1999 National Roadside Study (NRS)*, Truck Traffic Estimate Software Package (TTESP). Available in CD format.

Cannon, S. J., Kontuly, T., Miller, H. J., 1998. GIS-Based Emergency Response Planning in a Mexico–U.S. Border Community. *Applied Geographic Studies*. v 2, n 2, p 111–130.

Center for Chemical Process Safety. 1995. *Guidelines for Chemical Transportation Risk Analysis*. American Institute of chemical Engineers. AIChE, New York.

Champlain, B. 1999. Should There Be Response Time Limits Set for Dangerous Goods Emergencies? *Dangerous Goods News Letter*. Transport Canada. v 18 n 2.

Chen, Chi, Ren, Aizhu, 2003. Optimization of fire station locations using computer. Abstract. *Qinghua Daxue Xuebao/Journal of Tsinghua University*. Press of Tsinghua University. p 1390-1393

Church, R. and ReVelle, C. 1974. The maximal covering location problem. *Papers of the Regional Science Association*. v 32 p 101–118.

Cox, A.W., Lees, F.P., Ang, M.L. 1990. *Classification of Hazardous Locations*. IIGCHL, IChemE.

Desrochers, M., Marcotte, P., and Stan, M. 1996. The congested facility location problem. *Location Science*. v 3, p 9-23

Energy Educators of Ontario, 1993. *Energy Fact sheet*. Available from: <http://www.iclei.org/EFACTS/WIND.HTM>. Accessed May 2004.

References

Environment Canada, 2004. *Canadian Climate Normals or Averages 1971-2000.* <http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html>. Accessed May 2004

Erkut E. and Verter V. 1995 A. Hazardous Materials Logistics. In Drezner, Z. (Ed) *Facility Location, a Survey of Applications and Methods*. Springer Series in Operations Research, chapter 20, 467-506. Springer.

Erkut, E., Fenske, R., Kabanuk, S., Gardiner, Q., Davis, J. 2001. Improving the emergency service delivery in St. Albert. *INFOR.* v 39, n 4, p 416-433.

Fabiano, B., Currò, F., Palazzi, E., Pastorino, R., 2002. A framework for risk assessment and decision-making strategies in dangerous good transportation. *Journal of Hazardous Materials*. v 93, n 1, p 1–15.

Fewtrell P., Siddique A., 1998. *1994 Data on the Transport of Dangerous Substances*. WS Atkins Consultants Ltd. For the Health and Safety Executive, HSE books, UK. Available from: <http://www.hse.gov.uk/RESEARCH/crr_pdf/1998/crr98165.pdf>. Accessed May, 2004.

Firescope, INC, 1996. *Fire Station Location Study for the City of Melrose.* Available from: <http://www.melrose-firefighters.org/study.htm> Accessed May, 2004.

Frank, W. C., Thill, J-C., Batta, R. 2000. Spatial decision support system for hazardous material truck routing. *Transportation Research* Part C: Emerging Technologies. v 8, n 1-6, p 337-359. Elsevier.

GeoGratis. 2004. *National Atlas Base Maps*. Available from: <http://atlas.gc.ca/site/english/data_services/free_data.html>. Accessed May 2004.

References

Gorys, Julius M. L. 1987. The Intercity Carriage of Dangerous Goods in the Province of Ontario. Abstract. *Logistics and Transportation Review*. v 23, n3, p 307–325.

Hancock, K., M. Abkowitz, and M. Lepofsky. 1993. Assessing Hazardous Materials Emergency Response Capability: Methodological Development and Application. *Transportation Research Board*.

Hansen, P., Peeters, D., Thisse, J.-F. 1983. Public facility location modules. In Locational Analysis of Public Facilities.

Howell, M. 2004. City not ready for chemical, biological terrorism. *The Vancouver Courier*. Available from: <http://www.vancourier.com/032202/news/032202nn5.html> Accessed May, 2004.

Kara B. Y. Verter V. 2004. Designing a Road Network for Hazardous Materials Transportation. *Transportation Science*. v 38, n 2, p 188–196.

Khan, F. I., & Abbasi, S. A., 1999.. Major accidents in process industries and an analysis of their causes and consequences. *Journal of Loss Prevention in Process Industries*. v12, n 5, p 361–378.

KPMG Canada. 1999. Fire Station Location and Fire/Ambulance Study for City of Toronto. Unpublished report.

Leonelli, P., Bonvicini, S., Spadoni, G. 2000. Hazardous materials transportation: a risk-analysis-based routing methodology. *Journal of Hazardous Materials.* v 71, n 1-3, p 283-300. Elsevier.

List, G. F. 1993. Siting emergency response teams: tradeoffs among response time, risk, risk equity and cost. In L N. Moses, D. Lindstrom (Eds), *Transportation of hazardous materials: Issues in Law, Social Science and Engineering*. p 117-133.

List, G. F. Mirchandani, P. B. Turnquist, M. A. and Zografos, K. G. 1991. Modeling and analysis for hazardous materials transportation: Risk analysis, routing/scheduling and facility location. *Transportation Science.* v 25, n 2, p 100–114.

List, G.F., Turnquist, M.A. 1998. Routing and Emergency-Response-Team Siting for High-Level Radioactive Waste Shipments. *IEEE Transactions on Engineering Management.* v 45, n 2, p 141-152.

Marianov, V. and ReVelle, C. S. 1998. Linear, non-approximated modules for finding best routes in hazardous environments. *Journal of the Operational Research Society*. v 49, n 2, p 157-164. Palgrave Macmillan.

Mazzola, Carl A., Addis, Robert P., and Emergency Management Laboratory, Oak Ridge Institute for Science and Education, Oak Ridge, TN. 1995. *Atmospheric Dispersion Modeling Resources*. Prepared for United States Department of Energy, Emergency Management Advisory Committee, Subcommittee on Consequence Assessment and Protective Actions. Available from: <http://www.msiac.dmso.mil/wmd_documents/ADMResources.pdf>. Accessed May 2004.

Ministry of Transportation of Ontario, Carrier Safety and Enforcement Branch. 2001. *Vehicle weight and dimension limits in Ontario*. Available from: <http://www.mto.gov.on.ca/english/trucks/weight/>. Accessed May 2004.

MTAS Consultants. 1997. *City of Chattanooga Fire Department Management Study*. Available from: <http://www.chattanooga.gov/fire/firestudy/> Accessed May, 2004.

References

National Fire Protection Agency. 1997. *NFPA 472 Standard for Professional Competence of Responders to Hazardous Materials Incidents*. Available from: <http://www.tnema.org/Library/Misc/472.pdf>. Accessed May, 2004.

National Fire Protection Agency. 2004. *NFPA Glossary of Terms*. Available from National Fire Protection Agency website: <http://www.nfpa.org/PDF/definitions.pdf?src=nfpa>. Accessed May, 2004.

National Transportation Safety Board, US. 1991. *Hazardous Overturn of a Tractor-Semitrailer (Cargo Tank) With the Release of Automotive Gasoline and Fire, Carmichael, California February 13, 1991*. Hazardous Materials Accident Report, Summary. Available at <http://www.ntsb.gov/publictn/1991/HZM9101.htm>. Accessed May, 2004.

Nicolet-Monnier, M., Gheorghe, A. V. 1996. *Quantitative Risk Assessment of Hazardous Materials Transport Systems : Rail, Road, Pipelines and Ship*. Kluwer Academic Publishers, Dordrecht, Hardbound.

Office of the Fire Marshal. 1998. *Public Fire Safety Guidelines*, Section: Emergency Responses, Subject: Selecting A Hazardous Material Response Capability. Ministry of Public Safety And Security Ontario, Canada. Available from: <http://www.ofm.gov.on.ca/english/fireprotection/munguide/04-82-01.asp >. Accessed May, 2004.

Office of the Fire Marshal. 2003. *Terrorism/Hazardous Materials Awareness for First Responders in Ontario, Self-Study*. Ministry of Public Safety And Security Ontario, Canada. Available from: <http://www.ofm.gov.on.ca/english/multi-agency/TerrorHazmat/default.asp>. Accessed May, 2004.

References

Organization for Economic Co-operation and Development. 2004. *Transport of Dangerous Goods through road tunnels Quantitative Risk Assessment Model*. Unpublished User Guide

Parentela, E. M., Sathisan, S. K. 1998. . Evaluation of emergency preparedness for hazardous materials transport. *Proceedings of the International Conference on Computer Simulation in Risk Analysis and Hazard Mitigation*, Valencia, Spain, p 147-156.

Ray Barton Associates, DS Lea Consultants Ltd., Fred Nix, Research and Traffic Group 2000. *Ontario freight transportation system study*. Final report. Prepared for Transport Canada, Ontario Region.

ReVelle, C. S., Cohon, J. L. and Shobrys, D. 1991. Simultaneous siting and routing in the disposal of hazardous wastes. *Transportation Science*. v 25, p 138-145.

Rew, P.,J., Deaves, S., M., Lines, I. G. 1996. *Review of Flash Fire Modeling*. W. S. Atkins for the UK Health and Safety executive. Available from: <http://www.hse.gov.uk/research/crr_pdf/1996/crr96094.pdf>. Accessed May 2004

Rew, P.J., Spencer, H., Daycock, J. 2000. Off-site ignition probability of flammable gasses. *Journal of Hazardous Materials.* v 71, p 409-422

Rhyne, William R. 1994. *Hazardous Materials Transportation Risk Analysis, Quantitative Approaches for Truck and Train*. John Wiley & Sons Inc.

Rowe, W. D. 1983. *Risk assessment processes for hazardous materials transportation*. Transportation Research Board, National research council. Washington D.C.

Rushton, G. 1979. *Optimal location of Facilities*. COMPress, Inc., Wentworth, N. H.

Russell, E. R., Harwood, D. 1993. Procedures for the Development of Estimated Truck Accident Rates and Release Probabilities for Use in Hazmat Routing Analysis. In Saccomanno F. and Cassidy k. (Eds) *Transportation of Dangerous Goods: Assessing the Risk*. Institute for Risk research.

Saccomanno F.F., Button N.P. and Assar R. Al, 1998. *Release and Fire Incidents Rates for the Transport of Dangerous Goods through Road Tunnels and Surface Route*. Final Report. Unpublished report, Prepared for OECD/PIARC/EU Project No. ERS2

Saccomanno, F., Shortreed, J. H., and Van Aerde, M. 1989. *Assessing the Risk of Transporting Dangerous Goods By Truck and Rail, Part 2*. Institute for Risk research, university of waterloo, Canadian pacific Railways, and the University Research Incentive Fund.

Saccomanno, F.F., Allen, B. 1988. Locating emergency response capability for dangerous goods incidents on a road network. *Transportation Research Record.* v 1193, p 1-9

San Bernardino County Fire Department. 2004. *Hazardous Materials Response Team*. Hazardous Materials Division, Emergency Response Program. Available from: <http://www.sbcfire.org/hazmat/ER.asp> Accessed May, 2004.

Schilling DA, Vaidyanathan J, Barkhi R. 1993. A review of covering problems in facility location. *Location Science*. v 1, p 25–55.

Simmons, J.A. 1974. *Risk Assessment of Storage and Transportation of Liquified Natural Gas and LP-Gas*. Final report. US Environmental Protection Agency. PB247 415.

References

Sivakumar, R. A., Batta, R. and Karwan, M. H. 1995. A multiple route conditional risk module for transporting hazardous materials. *INFOR*. v 33, n 1, p 20-34. ABI Inform.

Smeby L., Jr. 1997. Justifying a Haz Mat Team. In National Fire Protection Agency, *Hazardous Material Response Handbook*.

Spadoni G., Leonelli P., Verlicchi P. and Fiore R., 1995. A numerical Procedure for Assessing Risks from Road Transport of Dangerous Substances. *Journal of Loss Prevention in the Process Industries*. v 8, n 4, p 245-252.

State of Wisconsin, Legislative Audit Bureau (2002) *An Evaluation, Regional Hazardous Materials Response Teams*. Department of Military Affairs. Available from: <http://www.legis.state.wi.us/lab/Reports/02-1full.pdf> Accessed May, 2004.

Statistics Canada, 2003. 2001Census data, Population and Dwelling Counts. Available from: <http://www12.statcan.ca/english/census01/products/standard/popdwell/Table-CSD-P.cfm?PR=35&T=2&SR=1&S=1&O=A>. Accessed April 2003

Technica Ltd. 1985. Study into the risks from transportation of liquid chlorine and ammonia in the Rijnmond area. Prepared for Dienst Centraal Milieubeheer Rijnmond. (DCMR)

The Weather Network, 2004. Weather Statistics, North America. Web site. <http://www.theweathernetwork.com/weather/stats/north_america.htm>. Accessed May 2004

TNO Bureau for Industrial Safety, Netherlands Organization for Applied Scientific Research. *Methods for the Determination of Possible Damage to People and*

Objects Resulting from Releases of Hazardous Materials. The Green Book. Rijswijk, the Netherlands: TNO (Commissioned by Directorate-General of Labour), 1992.

Toregas, C., Swain, R. ReVelle, C. and Bergman, L. 1971. The Location of Emergency Service Facilities. *Operations Research*. v 19, p 1363-1373.

Transport Canada, U.S. Department of Transportation, and Secretary of Transport and Communication of Mexico. 2000. *Emergency Response Guidebook 2000.* Available from: <http://www.tc.gc.ca/canutec/en/guide/guide-e.htm> Accessed May, 2004.

Transport Canada. 2002. *Statistics on Dangerous Goods Transported*. <http://www.tc.gc.ca/tdg/info/flowstats_e.htm>. The Transport Dangerous Goods Directorate. Last updated: 2001-12-10. Accessed 2002.

Transport Canada. 2003. *Transportation in Canada 2003 Annual Report*. Available from: < http://www.tc.gc.ca/pol/en/Report/anre2003/4A_e.htm>. Accessed May, 2004.

Transport Canada.1992. *Transportation of Dangerous Goods Act, 1992, Transportation of Dangerous Goods Regulations, Clear Language*. Available from: <http://www.tc.gc.ca/acts-regulations/GENERAL/T/tdg/regulations/tdg001/part_1.htm>. Accessed May, 2004.

Transport Dangerous Goods Directorate. 2000. *DGAIS, Dangerous Goods Accident Information System, 1988-2000*. Transport Canada. Retrieved from University of Waterloo, Tri University Data Resources. Available from: <http://tdr.uoguelph.ca.proxy.lib.uwaterloo.ca/DRC/DATA/NRENV/DGAIS/2002/

dgais2002.html>. Accessed May 2004. Access restricted to University of Waterloo affiliates.

Transport Dangerous Goods Directorate. 2004. *DGAIS, Dangerous Goods Accident Information System.* Documentation file. Transport Canada. Available form: <http://www.statcan.ca/english/Dli/Metadata/dgais/readme98.pdf>. Accessed May 2004.

Triantaphyllou E. 2000. *Multi-Criteria Decision Making Methods: A Comparative Study.* Kluwer Academic Publishers. Applied Optimization Series, Vol. 44.

TriData Corporation of Arlington, Virginia, US. 2001. *Multijurisdictional Fire Service Study for City of Cudahy and City OF South Milwaukee*. Final Report. Available at: <http://www.ci.south-milwaukee.wi.us/firestudy.htm>. Accessed May, 2004.

UK Health and Safety Executive. 1991. *Major Hazard Aspect of the Transport of Dangerous Substances*. Advisory Committee on Dangerous Substances, Health and Safety Committee, London. HMSO.

United States Fire Administration. Undated. *Hazardous Materials Response Technology Assessment manual*. Available from: <http://www.usfa.fema.gov/downloads/pdf/publications/fa-199.pdf>. Accessed May, 2004.

US Federal Emergency Management Agency. 1989. *Gasoline Tanker Incidents in Chicago, Illinois and Fairfax County, Virginia, Case Studies in Hazardous Materials Planning*. United States Fire Administration Technical Report Series. Available from: <http://www.interfire.com/res_file/pdf/Tr-032.pdf>. Accessed May, 2004.

References

US Federal Emergency Management Agency. 1998. *Guide to developing effective standard operating procedures for fire and EMS departments*. US fire administration. Available from: <http://www.usfa.fema.gov/downloads/pdf/publications/fa-197.pdf> Accessed May, 2004.

US Code of Federal Regulations. 2003. *CFR Title 49-Transportation*, Chapter I-Research and Special Programs Administration, Department of Transportation, Part 110-Hazardous Materials Public Sector Training and Planning Grants, Activities Eligible for Funding. Available from: <http://a257.g.akamaitech.net/7/257/2422/05dec20031700/edocket.access.gpo.gov/cfr_2003/octqtr/pdf/49cfr110.40.pdf>. Accessed May, 2004.

US Department of Transportation, Bureau of Transportation Statistics, U.S. Department of Commerce, Census Bureau; Statistics Canada; Transport Canada; Instituto Mexicano del Transporte; Instituto Nacional de Estadística, Geografía e Informática; and Secretaría de Comunicaciones y Transportes. 2000. *North American Transportation in Figures*. BTS00-05, Washington, DC. Available from: <http://www.statcan.ca/english/freepub/50-501-XIE/free.htm>. Accessed May, 2004.

US Department of Transportation, Research and Special Programs Administration. 1997. *Hazardous Materials: Cargo Tank Motor Vehicles in Liquefied Compressed Gas Service; Revisions and Response to Petitions for Reconsideration*. Final rule; response to petitions for reconsideration. Federal Register, Vol. 62, No. 159 Rules and Regulations. < http://hazmat.dot.gov/rules/hm225_f1.htm >. Accessed May, 2004.

US Department of Transportation. 2000. *Departmentwide Program Evaluation of the Hazardous Materials Transportation Programs*. Final report. Available from: <http://hazmat.dot.gov/hmpe_report.pdf>. Accessed May, 2004.

US Environmental Protection Agency, National Oceanic and Atmospheric Administration. 1999. *ALOHA User's Manual*. Available from: <http://www.epa.gov/ceppo/cameo/pubs/aloha.pdf>. Accessed May, 2004.

US Environmental Protection Agency. 1990, *Hazmat Team Planning Guidance*. EPA 540/G-90/003 Directive: 9285.3-05. Available from: <http://web.em.doe.gov/otem/epadoc.pdf>. Accessed May, 2004.

US Environmental Protection Agency. 1999. Risk Management Program Guide for Offsite Consequence Analysis. Office of Solid Waste and Emergency Response (5104), 550-B-99-009. Available from: <http://www.epa.gov/swercepp/pubs/oca/oca-all.pdf>. Accessed May, 2004.

US Federal Emergency Management Administration, U.S. Department of Transportation and U.S. Environmental Protection Agency. 1989. *Handbook of Chemical Hazard Analysis Procedures*. Available from: <http://www.epa.gov/cgi-bin/claritgw?op-Display&document=clserv:OSWER:2629;&rank=4&template=epa>. Accessed May, 2004.

Wilson, F. R., Cantin, L., Bisson, B. G. 1990. Emergency Response System for Dangerous Goods Movements by Highways. *Journal of Transportation Engineering*. v 116, n 6, p 789-794.

References

Zeimet D., Ballard D. 2000. *Hazardous Material Behavior and Emergency Response Operations*. The American Society of Safety Engineers.

Zografos, K. G., Androutsopoulos, K. N. 2004. A heuristic algorithm for solving hazardous materials distribution problems. *European Journal of Operational Research*. v 152, n 2, p 507-519. Elsevier.

Zografos, K. G., Vasilakis, G. M., Giannouli, I. M. 2000. Methodological framework for developing decision support systems (DSS) for hazardous materials emergency response operations, *Journal of Hazardous Materials.* v 71, p 503-521.

Appendices

APPENDIX A: REVIEW OF HAZMAT MOVEMENTS AND ACCIDENTS IN CANADA

HazMat are transported in great amounts on our transportation system and with it comes the great potential of high-risk to both humans and environment. Table A-1 shows approximate Canadian annual number of HazMat shipments and tonnage by mode of transportation (Transport Canada 2002). According to Transport Canada 1998 annual report, every year over 27 million HazMat shipments are transported across Canada. About 25 million of them (92.55%) are made by road with total tonnage of over 128 million ton.

Table A-1: Canadian annual number of HazMat shipments and tonnage by mode

Mode	Shipments		Tonnage	
Air	1,490,000	5.52%	92,000	0.04%
Marine (no bulk)	10,000	0.04%	71,300,000	31.00%
Rail	510,000	1.89%	29,900,000	13.00%
Road	24,990,000	92.55%	128,708,000	55.96%

Table A-2 shows the HazMat road tonnage by province (Transport Canada 2002). From the table, it is shown that Ontario comes second after Alberta in HazMat movements.

Table A-2: Road tonnage by province

	leaving	**entering**	**intra**
NF	0.12%	0.09%	1.16%
PE	0.01%	0.34%	0.18%
NS	1.35%	0.73%	6.02%
NB	1.44%	2.10%	3.07%
QC	8.51%	5.63%	16.50%
ON	**8.11%**	**9.68%**	**27.83%**
MB	2.04%	3.35%	4.29%
SK	3.83%	3.69%	6.40%
AB	10.30%	4.70%	32.80%
BC	3.74%	5.28%	12.06%
NT	0.10%	0.73%	1.51%
YK	0.01%	0.35%	0.06%
US	4.49%	7.38%	0

The transportation of HazMat by air, marine, rail and road is regulated under the federal "Transportation of Dangerous Goods Act", 1992. Also the "Transportation of Dangerous Goods Regulations" establishes the safety requirement for the transportation of dangerous goods.

HazMat Incidents in Transport

Transport Canada statistics (Transport Canada 1998) shows that between 1989 and 1997 the number of reported HazMat road accidents ranges between 103 to 239 per year with an average of 156 (Table A-3). Number of deaths and Injuries Caused by HazMat at Reportable Accidents for 1988 – 1998 are given in Table A-4.

Table A-3: Reportable accidents involving HazMat by mode of transport

Reportable Accidents Involving HazMat by Mode of Transport, 1988 - 1998						
	In Transit				Not In	
Year	Road	Rail	Air	*Marine	Transit	Total
1988	155	11	0	1	323	490
1989	192	29	3	3	334	561
1990	183	17	2	0	194	396
1991	155	27	4	2	251	439
1992	140	25	0	1	228	394
1993	103	25	1	0	113	242
1994	114	30	1	0	145	290
1995	109	19	3	0	205	336
1996	239	35	9	1	237	521
1997	166	16	6	1	194	383
Average	156	23	3	1	222	405
1998	184	14	4	0	234	436

*The TDG program does not cover HazMat transported in bulk on ships or by pipeline.
Source: transport Canada, Dangerous Goods Accident Information System

Table A-4: Number of deaths and number and severity of injuries

Deaths and Injuries Caused by HazMat at Reportable Accidents, 1988 - 1998					
	Deaths	Injuries Due to HazMat			
Year	Due to DG	Major	Moderate	Minor	Total
1988	6	-	-	-	65
1989	3	21	50	13	84
1990	0	8	42	0	50
1991	1	9	9	21	39
1992	0	3	3	34	40
1993	18*	1	2	14	17
1994	0	0	3	29	32
1995	0	3	58	2	63
1996	1	2	10	16	28
1997	2	15	14	4	33
Average	3.1	6.9	21.2	14.8	45.1
1998	2	1	19	8	28

*All 18 deaths are from the same bus-truck collision, Lac Bouchette (Quebec)
- Minor injuries refer to those injuries that require first-aid treatment, moderate injuries require emergency hospital treatment, and major injuries require overnight hospitalization

Table A-5 shows calls to CANUTEC that resulted in an emergency by province from 1991 till 1999. As shown in Table A-5, Ontario comes first in number of reported HazMat incidents that has resulted in an emergency, with (in some years) more than double the number of calls of the second province (Quebec).

Table A-5: Calls to CANUTEC that resulted in an emergency

Location	1999	1998	1997	1996	1995	1994	1993	1992	1991
British-Columbia	86	127	123	172	168	27	161	188	193
Alberta	92	115	135	101	133	105	99	101	97
Saskatchewan	22	34	26	29	28	29	21	27	26
Manitoba	30	38	42	38	52	35	39	40	35
Ontario	331	387	324	377	411	344	316	338	311
Quebec	202	188	193	183	172	129	121	154	111
New-Brunswick	26	26	33	28	25	36	32	74	55
Nova-Scotia	26	28	26	28	31	21	32	19	28
Prince-Edward-Island	2	3	0	2	1	0	2	1	3
Newfoundland	0	7	8	8	12	12	9	14	10
Northwest Terr.	1	0	5	1	0	1	3	0	1
Yukon Terr.	3	0	0	0	3	0	2	4	0
U.S.A.	34	46	37	23	23	24	14	28	12
International	0	5	2	4	6	1	2	1	0

Due to different requirements by Transport Canada in reporting a HazMat related accidents, the number of reportable accidents according to Transport Canada differs from the number of calls to CANUTEC. The difference represent accidents which were filed as voluntary accident reports falling outside the accident reporting threshold requirement by TDG regulations.

Figure A-1 shows the number of Transport Canada reportable accidents involving HazMat between 1989 and 1998 (Transport Canada 1998).

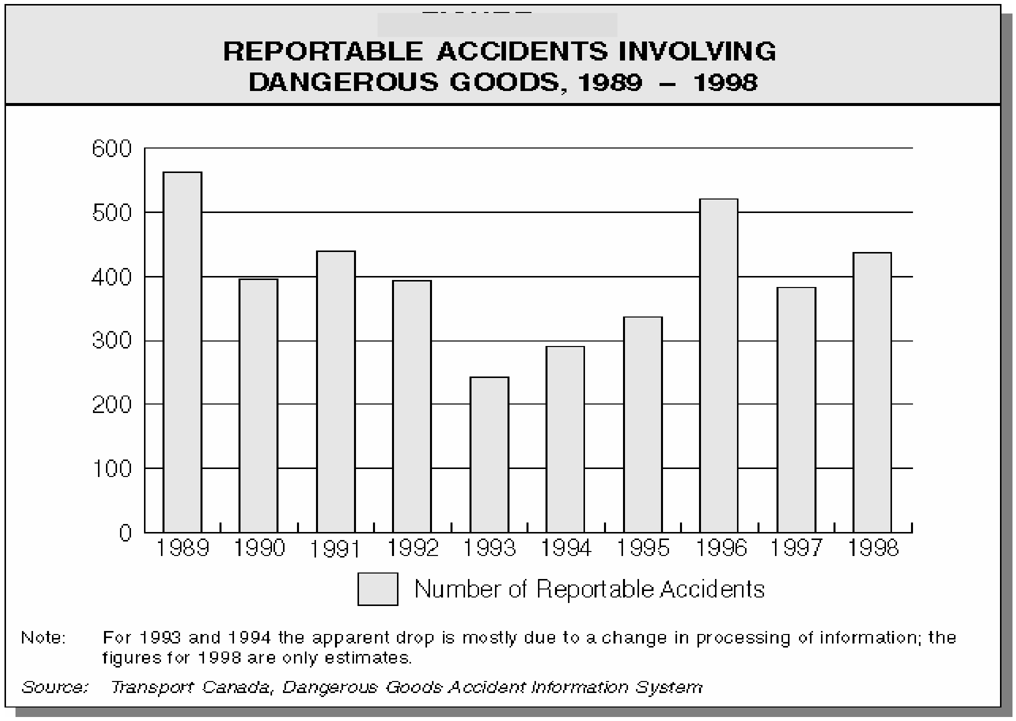


Figure A-1: Number of reportable accidents involving HazMat between 1989 and 1998 (Transport Canada 1998 annual report)

References

Transport Canada. 2002. *Statistics on Dangerous Goods Transported.* <http://www.tc.gc.ca/tdg/info/flowstats_e.htm>. The Transport Dangerous Goods Directorate. Last updated: 2001-12-10. Accessed 2002

Transport Canada. 1998. *Transportation in Canada 1998 Annual Report.*

APPENDIX B: HAZMAT TEAM

The National Fire Protection Agency (2004) defines the hazardous material team as an organized group of trained response personnel, operating under an emergency response plan and appropriate standard operating procedures, who handle and control actual or potential leaks or spills of hazardous materials requiring possible approach to the material. The team members respond to releases or potential releases of hazardous materials for the purpose of control or stabilization of the incident. HazMat teams are equipped with special personal protective equipment as well as containment and decontamination equipments.

The HazMat team can engage in many activities during an incident, mainly, identification, confinement, and /or containment of the hazardous material. Special personnel training is needed for to response to hazardous materials incident. NFPA defines the following five levels of training for responding to HazMat incident (US Federal Emergency Management Administration 1998, National Fire Protection Agency 1997):

1. **First Responder Awareness**–Individuals likely to witness or discover the release of a hazardous material. Trained to initiate the appropriate response and take no further action.
2. **First Responder Operations**–Respond to releases or potential releases of hazardous substances as part of the initial response. Expected to take defensive

actions without trying to stop the release, for the purpose of protecting persons, property, and the environment.

3. **Hazardous Materials Technician**–Respond to a hazardous materials incident for the purpose of stopping the release. These individuals are often members of a HazMat team.
4. **Hazardous Materials Specialist**–Respond with and support hazardous materials technicians. Possess specialized knowledge of chemical hazards or container characteristics.
5. **On-scene Incident Commander**–Assume control of the incident beyond the first responder awareness level. This individual must possess minimum training at the first responder operations level with additional knowledge of state, local, and federal response plans.

Personal protective equipment provided to shield or isolate a responder from the chemical, physical, and thermal hazard that can be encountered at a hazardous material incident. Personal protective equipment includes both personal protective clothing and respiratory protection. Adequate personal protective equipment should protect the respiratory system, skin, eyes, face, hands, feet, head, body, and hearing. An example of personal protection equipment is shown in Figure B-1.

Appendix B

Figure B-1: HazMat personal protection equipment

Figure B-2: HazMat emergency response vehicle

Appendix B

Figure B-2 and Figure B-3, A & B show HazMat emergency response vehicle and emergency response team at work respectively.

A.

B.

Figure B-3: Emergency response team at work

Appendix B

Lesak (1999) defined the following HazMat response goals:

1. Isolation	a) Perimeter establishment b) Zoning (zone establishment) c) Initial public protection d) Denial of entry e) Withdrawal
2. Notification	a) Establish communication links b) Request assistance c) Incident level identification d) Emergency public information
3. Identification	a) Recognition and identification b) Data retrieval c) Interview d) Review of plans and surveys e) Reconnaissance f) Monitoring g) Sampling
4. Protection	a) Secondary public protection b) Personal protection equipment c) Decontamination

	d) Pre-entry briefing e) EMS and fire assessment f) Safety assessment g) Pre-entry medical monitoring h) Reassess zones
5. Spill Control	a) Gas/air releases: Ventilation, Dissolution, Dispersion, Diversion b) Liquid/surface releases: Diking, Diversion, Retention, Adsorption, Neutralisation, Absorption c) Liquid/water releases: Damming, Diverting, Booming, Absorption d) Solid/surface releases: Planking
6. Leak control	a) Direct leak control: Plugging, Patching, Overpacking, Crimping, Product transfer, Valve actuation b) Indirect leak control: Remote shut-offs, Emergency shut-offs, Product transfer, Product displacement
7. Recovery/ termination	a) Operation recovery: Oversight of cleanup, Oversight of product transfer, Oversight of container righting and handling, Demobilization b) Administrative recovery: Inventory control, Restocking, Financial restitution

Appendix B

Local authorities bare the responsibility of providing enough HazMat emergency response for the community. HazMat teams are usually hosted within fire stations. HazMat teams respond to HazMat incidents onsite as well as in transit. However, many industries have their own HazMat response capabilities. There are also some privately owned and operated HazMat teams. Transport Canada (2004) lists various Emergency Response Contractors and associations located across Canada offering different services for various types of HazMat and offer different levels of response capability. Some of these contractors may have a national response capability.

The Ontario Fire Service Section 21 Committee issued Guidance Note #26 in March, 1997, dealing with fire department responses for hazardous materials. This guidance note states that regardless of the level of response offered by a fire department, all responding personnel must be trained to the First Responder, Awareness Level of NFPA 472, as a minimum.

References

Lesak, D. M. 1999. *Hazardous Materials Strategies and Tactics*. Brady/Prentice Hall.

National Fire Protection Agency. 1997. *NFPA 472 Standard for Professional Competence of Responders to Hazardous Materials Incidents*. Available from: <http://www.tnema.org/Library/Misc/472.pdf>. Accessed May, 2004.

National Fire Protection Agency. 2004. *NFPA Glossary of Terms*. Available from National Fire Protection Agency website: <http://www.nfpa.org/PDF/definitions.pdf?src=nfpa>. Accessed May, 2004.

Transport Canada. 2004. *Emergency Response Contractors and associations*. Webpage. Available at: <http://www.tc.gc.ca/tdg/erc/contractor.asp>. Accessed May 2004.

US Federal Emergency Management Agency. 1998. *Guide to developing effective standard operating procedures for fire and EMS departments*. US fire administration. Available from: <http://www.usfa.fema.gov/downloads/pdf/publications/fa-197.pdf> Accessed May, 2004.

APPENDIX C: ALOHA

ALOHA is an air dispersion model to evaluate hazardous chemical release scenarios and predict dispersion. ALOHA stands for the Areal Locations of Hazardous Atmospheres. It is a computer modeling tool for estimating the movement and dispersion of hazardous chemical gases. ALOHA is intended primarily for rapid deployment by responders, as well as for use in emergency preplanning.

ALOHA can predict the rates at which gases may escape into the atmosphere from broken gas pipes, leaking tanks, and evaporating puddles. Then, it can predict how a hazardous gas cloud might disperse in the atmosphere after an accidental chemical release. It incorporates source strength, as well as Gaussian and heavy gas dispersion models and an extensive chemical property library.

ALOHA requires different parameters for modeling gas dispersion such as HazMat type, discharge rate, release duration, immediate dangerous to health and life (IDHL) level for toxic materials (or Lower Flammability Level for flammable materials) weather and terrain conditions. ALOHA uses the information about type of HazMat released, rate of release, and weather conditions.

ALOHA gives output is in both text and graphic form, and includes a "footprint" plot of the area downwind of a release, where concentrations may exceed a user-set threshold level. ALOHA can accept weather data transmitted from portable monitoring stations and requires the following input meteorological and topographical data: mean wind speed, wind direction, and air temperature; ground roughness length (user can choose between "open country" and "urban or forest," or can enter a specific value); cloud cover in tenths; and relative humidity.

ALOHA can model gas dispersion as Gaussian puff and plume, as well as heavy gas dispersion. Based on the following dispersion Algorithms:

(1) Modified time-dependent Gaussian equation, based on:

(a) Hanna, S.R., Briggs, G.A., and Hosker, R.P., Jr., 1982, "Handbook on Atmospheric Diffusion," Report DOE/TIC-11223, Oak Ridge Technical Information Center, U.S. Department of Energy.

(b) Palazzi, E., DeFaveri, M., Fumarola, G., and Ferraiolo, G., 1982, "Diffusion from a Steady Source of Short Duration," *Atmospheric Environment* 16 (12): 2785-2790.

(c) Beals, G.A., 1971, "Guide to local diffusion of air pollutants." Technical Report 214, U.S. Air Force Weather Service, Scott Air Force Base, IL.

(2) Heavy gas dispersion model based on:

Havens, J.A., and Spicer, T. O., 1985, "Development of an Atmospheric Dispersion Model for Heavier-Than-Air Gas Mixtures," Volume I, Report CG-D-22-85 to U.S. Coast Guard, Washington, D.C., Office of Research and Development, U.S. Coast Guard, Department of Transportation. (DEGADIS model)

Appendix C

ALOHA can predict the area within which a person might experience an immediate serious health impact from contact with more than a certain concentration of a toxic gas. This concentration is called the level of concern, or LOC. ALOHA can also be used to predict the area where a flammable gas may explode. ALOHA uses the physical characteristics of the released chemical and the real-time circumstances of the release scenario to predict the dispersion of a hazardous gas cloud.

ALOHA was developed as a response tool in 1982 by The National Oceanic and Atmospheric Administration or NOAA. Over the years, several academic institutions and response organizations helped in its development and refinement. Its use by emergency responders increased as the benefits of its ease of use and speed of calculations were demonstrated. Since late 1987 ALOHA has been co-developed with US Environmental Protection Agency, Chemical Emergency Preparedness and Prevention Office. In January 1991, a completely rewritten ALOHA was distributed. It included new calculations to estimate source strength discharge rate and to predict the dispersion of heavier-than-air gases. ALOHA continues to be refined.

ALOHA could be downloaded free of charge from the US Environmental Protection Agency website

http://www.epa.gov/ceppo/cameo/aloha.htm

Further information and technical details about ALOHA could be found in “ALOHA User’s Manual” published by US Environmental Protection Agency, 1999.

APPENDIX D: HAZMAT TEAM RISK-BASED LOCATION OPTIMIZATION MODEL (HAZMAT-RISKLOM), USER MANUAL

2004

Ghada Mahmoud Hamouda

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

Appendix D

DISCLAIMER

Ghada Hamouda and University of Waterloo make no warranty, expressed or implied, to users of the programs included in this HazMat teams Risk-based Location Optimization Model (HazMat-RiskLOM), and accept no responsibility for its use. User of the HazMat-RiskLOM assume sole responsibility for determining the appropriateness of its use in any particular application, for any conclusions drawn from the results of its use, and for any action taken or not taken as a result of analyses performed using this model. Users are warned that this HazMat-RiskLOM is intended for use only by those competent in the field of HazMat risk assessment and emergency response planning, and is intended only to supplement the informed judgment of the qualified user.

Appendix D

WELCOME TO HAZMAT-RISKLOM

Welcome to HazMat-RiskLOM. This manual is relative to version 1.0 of a software package written by Ghada Hamouda as part of a PhD research. This work has been performed under the supervision of professors F Saccomanno and L. Fu from University of waterloo. It has been funded partly by The Ontario Graduate Scholarship Program (OGS) and The Natural Sciences and Engineering Research Council (NSERC) of Canada.

Program Purpose

HazMat-RiskLOM (**HazMat** team **Risk**-Based **L**ocation **O**ptimization **M**odel) is a Windows-based computer program designed especially for use by HazMat emergency response planners. HazMat-RiskLOM was developed to be a decision support tool to investigate different options in planning transport-related HazMat emergency response. HazMat-RBLOM can be used to plan HazMat team locations on a road network and to investigate different HazMat emergency response policies.

HazMat-RiskLOM's Scope

The HazMat-RiskLOM is limited to the following:

1) The model can locate up to 12 HazMat teams simultaneously.

2) Risk modeling is limited to four HazMat types representing four classes of HazMat and four release events. The four HazMat types (*k*) are:

1. Toxic liquefied gases: represented by Ammonia
2. Flammable liquefied petroleum gases (LPG): represented by Propane
3. flammable liquids: represented by Gasoline
4. Toxic/corrosive liquids

The four release events (*r*) are:

1. Large spill
2. Small spill
3. Large leak
4. Small leak

Table 1 lists considered release scenarios.

Table 1: Release scenarios

Release scenario	HazMat type (*k*)	Release type (*r*)
1	1. Ammonia	1. Large spill
2	1. Ammonia	2. Small spill
3	1. Ammonia	3. Large leak
4	1. Ammonia	4. Small leak
5	2. Propane	1. Large spill
6	2. Propane	2. Small spill
7	2. Propane	3. Large leak
8	2. Propane	4. Small leak
9	3. Gasoline	1. Large spill
10	3. Gasoline	2. Small spill
11	3. Gasoline	3. Large leak
12	3. Gasoline	4. Small leak
13	4. Toxic liquids	1. Large spill
14	4. Toxic liquids	2. Small spill
15	4. Toxic liquids	3. Large leak
16	4. Toxic liquids	4. Small leak

3) The HazMat-RiskLOM allows the user to directly provide the HazMat truck traffic volume for a certain HazMat type *k* on link *l*. By giving users the capability of defining traffic volumes for specific HazMat types on certain links, users can utilize the model to study:

   - Certain type of HazMat on certain route (links)
   - Combination of different types of HazMats on certain routes
   - All types of HazMats on the whole network

   In situations that detailed data on HazMat movements are not available, the users can estimate HazMats traffic volumes using one of several option provided by the model.

Basic program organization

To use HazMat-RiskLOM, the user will typically perform the following basic steps:

1. Prepare road network data files in a compatible format to be used by the model.
2. Determine values for different input parameters (if different from model defaults)
3. Request the model to calculate fastest paths and associated risks
4. Enter information about number of HazMat teams to be located and number of best solutions you want to review
5. Request the model to locate teams either to minimize human risk or minimize environmental impact

Through a number of menus and pop-up windows, the user is asked to define available HazMat, movements, accidents, and releases data. The model uses the defined data to determine correspondent risk and HazMat team locations. The user can change different input parameter values and investigate the change in network risk or HazMat team locations.

Basic HazMat-RiskLOM operation menu is shown in (Figure 1) which include two top menu items:

1) **Import Data**: Choose items from the **Import Data** menu to enter information about road network nodes and links.
2) **Network**: Choose items from the **Network** menu to:
   a) Calculate response times using fastest path algorithm
   b) Calculate risks at network nodes
   c) Sit HazMat teams at certain locations
   d) Fined best risk-minimization HazMat team locations
   e) Find Hazmat teams locations using Genetic Algorithms for large problems
   f) Delete the existing network to be able to import a new network

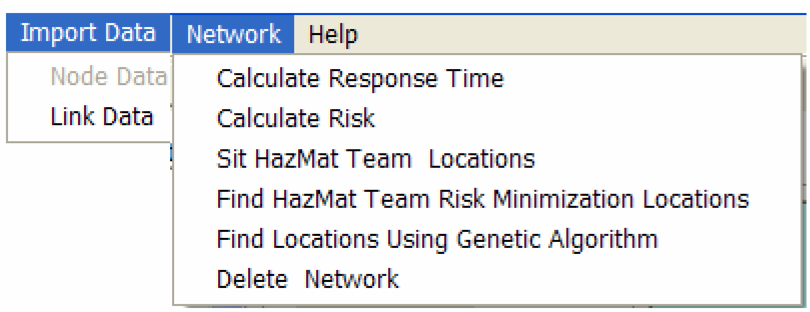


Figure 1: HazMat-RiskLOM menu bar

Appendix D

Installing HazMat-RiskLOM

Install the HazMat-RiskLOM package by copying the HazMat-RiskLOM.exe file as well as example data files and folders to your computer.

Appendix D

LEARNING THE BASICS

This Chapter contains a step-by-step illustration on how to use HazMat-RiskLOM as a emergency response planning tool.

Preparing input Files

The HazMat-RiskLOM requires that data is represented in two input files: 1) the network nodes file, and 2) the network links file. The files should be in text format with input fields separated by tabs.

Nodes represent major population concentrations and major intersections on the network as well as intermediate points on long arcs. The following seven attributes are needed for the node file:

1. Node_ID	A unique number that identifies each node. The assigned Node_IDs for different nodes must run sequential from 1 to total number of nodes, *nd.*
2. Xcor	Longitude position of the node.
3. Ycor	Latitude position of the node.
4. PopulationDenst	Population density at the node. One value that represent the average population density for the region represented by the node.
5. FireStation	Dummy variable

	= 1 if the node hosts fire station, =0 otherwise. Nodes with firs stations are considered candidate node for HazMat team locations.
6. Urban	Integer, = 1 if node is within urban area, = 2 if the node within rural area, and = 0 if unknown.
7. Intersection	Dummy variable = 1 if the node is an intersection or population center node, =0 otherwise

roads are represented as directed links. Every road segmant on the road network is represented by 2 links, one for each traffic direction. The following data fields (8 to 20) represent different link attributes:

8. Link_id	A unique number that identifies each link. Link_id can take any integer number.
9. Hnode_id	Node_ID of Link's head node (node from which traffic entering the link).
10. Tnode_id	Node_ID of Link's tale node (node to which traffic exiting the link).
11. L_Length	Link length in km.
12. L_PostedSpeed*	Posted speed on link (km/hr).

13. L_TravelTime*	Emergency vehicles actual travel time on Link (minutes). The user has the option of directly providing estimates of emergency vehicles travel time on links; otherwise, posted speed and link length will used to calculate free flow travel time on links.
14. L_AllVehiclesAADT**	Link average annual daily traffic for all vehicles (vehicles/day)
15. L_TruckAADT**	Link average annual daily traffic for trucks (vehicles/day)
16. L_AllDGsAADT**	Link average annual daily traffic for HazMat movements (vehicles/day)
17. L_FlamLqdAADT**	Link flammable liquids average annual daily traffic (vehicles/day)
18. L_ToxcLqdAADT**	Link toxic liquids average annual daily traffic (vehicles/day)
19. L_FlamGasAADT	Link flammable liquefied gases average annual daily traffic (vehicles/day)
20. L_ToxcGasAADT**	Link toxic liquefied gases average annual daily traffic (vehicles/day)

*Either 12 or 13 is needed
** Either 14, 15, 16, or 17-20 is needed

Start the program

As you use HazMat-RiskLOM, you'll enter information on a series of popup windows and dialog boxes to describe your problem. Start by running the file "HazMat-RiskLOM.exe". After a splash screen, an "Input options" window will open (Figure 2). Choose between two options for travel time estimation:

- Directly providing user estimates of emergency response vehicles on links
- Provide posted speed on links for the model to estimate travel times.

Choose one of the four presented options for HazMat movements calculations:

- HazMat AADT on links by HazMat type
- Total HazMat AADT on links
- Truck AADT on links
- All vehicles AADT on links

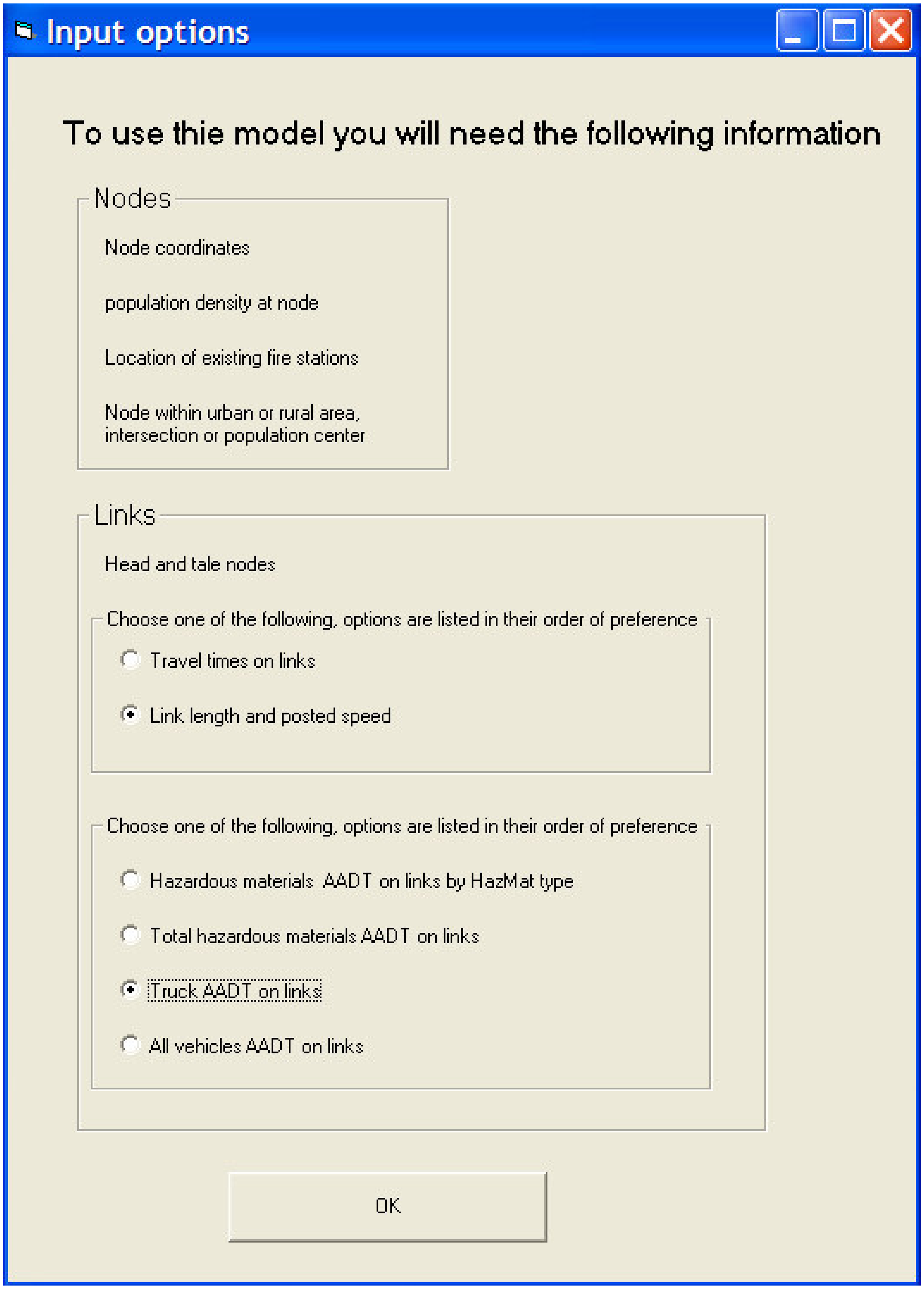


Figure 2: "Input options" window

Import Data

After selecting input options press “OK” button. The main program window “HazMat-RiskLOM’ will open (Figure 3). Select “Node data” from the “Input data” menu and using the dialog box, navigate through the files and folders to choose and open the node file. To import links data, select “Link data” from the “Input data” menu. From the dialog box, select and open the node file. The model uses nodes and links information and displays a representation of the network.

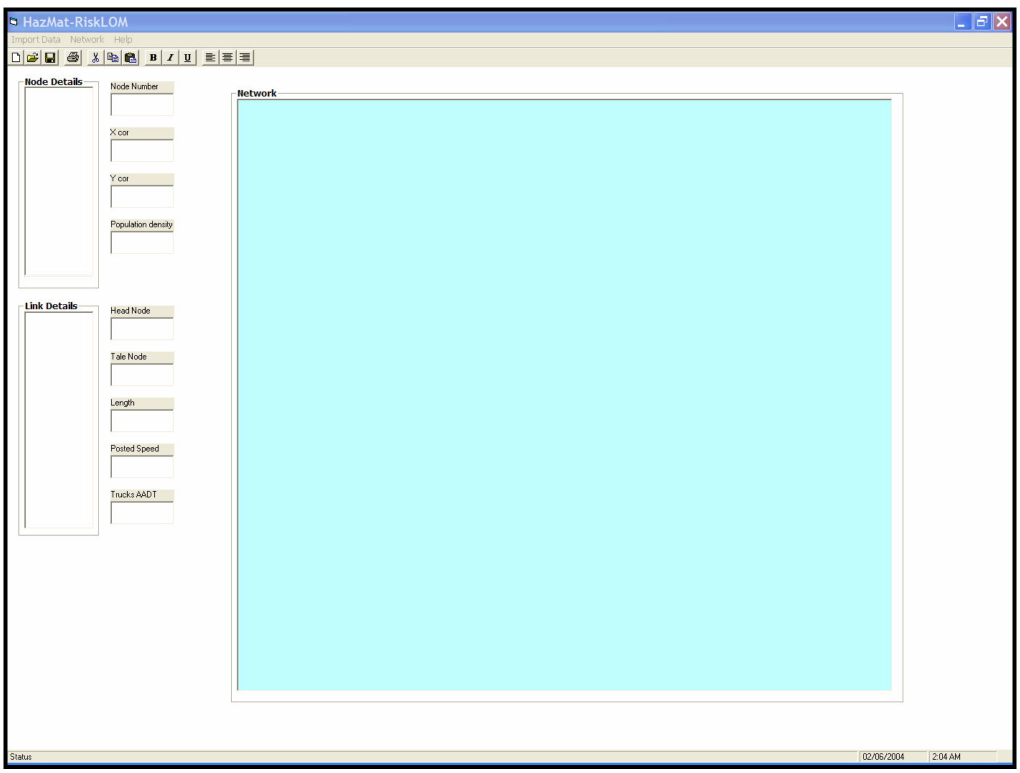


Figure 3: HazMat-RiskLOM main window

Response Time and Risk Calculations

Response times calculations

From “Network” menu select “Calculate response time”. The “Response Time” popup window (Figure 4) allows you to provide user-defined values for the dispatch time, mitigation time, maximum delay at intersection nodes, and delay factors on links.

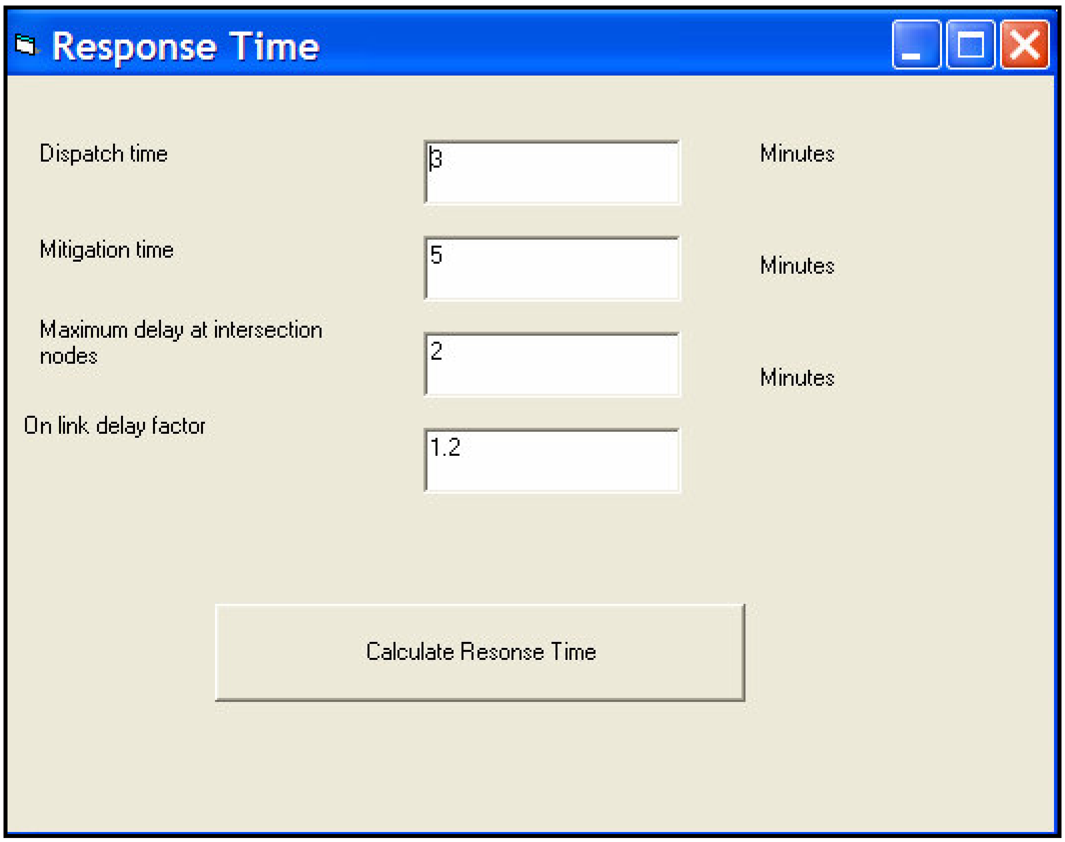


Figure 4: “Response time” window

Thesis values along with travel times on links are used to calculate response times for different network nodes using fastest path algorithm. You can change input parameters in the response time and see the resultant effect on risk estimates and HazMat team locations.

Risk calculations

For risk calculations, you will need to provide a run-time input data regarding HazMat traffic, accident and release rates. Default values for Ontario, Canada are provided, however, user defined values could be substituted. To calculate risk for different node network select "Calculate risk" from "Network" menu. Several popup windows will be displayed with default input parameters values used in risk calculations.

Traffic volumes representation and calculations:

The user has the option of providing any one of the following four movement data:

1) Detailed HazMat traffic movement for each HazMat type *k* on every link *l,* ($HazMat\_TRFC_l^k$). The following link attributes are used for this option:

    17. L_FlamLqdAADT

    18. L_ToxcLqdAADT

    19. L_FlamGasAADT

    20. L_ToxcGasAADT

    In this case, link attributes 14, 15, and 16 should not be presented.

2) Total of all HazMats' traffic volumes on every link (16. L_AllDGsAADT). In this case, link attributes 14, 15, and 17-20 should not be presented. The specific

HazMat type volumes on links are estimated according to the fraction of that HazMats type in the total HazMat traffic according to the following equation:

$$HazMat\_TRFC_l^k = \alpha^k * L\_AllDGsAADT$$

Where α^k is the fraction of HazMat type k in the whole HazMats traffic.

Table 2 shows estimates of α^k for different HazMat types transported by road reported by Transport Canada[11]. These values are provided in the TDQRA model as default values, however the user has the option of providing his/her own estimates of α^k .

Table 2: Percentage of top HazMat transported by road (by tonnage), reported by Transport Canada.

Classification K	Shipping name	percent	Total percent α^k
Flammable liquids	Gasoline	22.97	64.61
	Fuel Oil	17.53	
	Tars	7.82	
	Petroleum Crude Oil	6.69	
	Ethanol	2.92	
	Aviation fuel	1.58	
	Flammable Liquids preparations	1.51	
	Flammable Liquids n.o.s.	1.36	
	Paint	0.92	
	Resin Solutions	0.88	
	Medicines, n.o.s.	0.43	
Corrosive liquids	Corrosive Liquids n.o.s.	10.44	14.62
	Caustic Soda	2.18	
	Sulphuric Acid	1.60	
	Hydrochloric Acid	0.40	
Flammable liquefied gases	Propane	1.85	3.58
	Petroleum Gases	1.15	
	Butane	0.58	
Toxic liquefied gases	Ammonia	0.98	0.98
		Total	83.79
Other HazMat material (do not fall under the previous 4 classification of HazMat and/or transported in small amounts)			16.21

[11] Transport Canada http://www.tc.gc.ca/tdg/info/flowstats_e.htm

3) Total truck traffic volumes on every link, L_TruckAADT. In this case, link attributes 14, 16, and 17-20 should not be presented. Using a certain percentage β_l as the fraction of HazMats volumes in the whole truck volumes on link *l*, the model estimates the total HazMats volumes on links L_AllDGsAADT according to the following equation:

$$L\_AllDGsAADT = \beta * L\_TruckAADT$$

Having an estimate of L_AllDGsAADT, the model then estimates $HazMat\_TRFC_l^k$ as described in the previous option 2. The following equation combines the 2 steps:

$$HazMat\_TRFC_l^k = \alpha^k * \beta * L\_TruckAADT$$

We estimated a Canadian default value for β using Commercial Vehicles Road Side Survey (1995) data. The survey collected data at 148 survey sites spread across the 25,600 kilometers of the Survey Highway System (**SHS**). Two types of information were collected at each site:

- a 7 day count of trucks passing the site, classified by day, time and truck type
- interviews of a random sample of the passing trucks (80 questions in interview).

Combined, the 148 sites counted 1,040,163 trucks and interviewed 36,242 trucks (3.5%).

We extracted an estimate of the percentage of HazMat movements by ton for different HazMat classes from the "1995 Road Side Survey" data using "WesVarPC2.02" software[12].

Table 3 shows that HazMats accounts for 9.85% of all truck movements by ton on the survey roads. Although these estimates are based on truck movements on the survey roads, we can generally assume they are applicable for all truck traffic in Canada. So, generally we can assume a value of 9.85% for "β" factor.

Table 3: Estimated percentage of different HazMat types transported on Canadian roads (by ton)

Class	percent
1	0.08
2	1.20
3	5.09
4	0.30
5	0.75
6	0.13
7	0.09
8	0.97
9	0.12
Cargo includes dangerous goods, but unable to determine class	1.12
Total HazMat	9.85
Total Non-HazMat	90.15
Total	100.00

Again, this estimated value for the parameter β is provided as a Canadian default value and the user has the option of providing his/her own estimate.

[12] Developed by Westat, Main Campus 1650 Research Boulevard, Rockville, MD 20850, 301.251.1500

4) Total vehicle traffic volumes, L_AllVehiclesAADT. In this case, link attributes 15, 16, and 17-20 should not be presented. This final option should be used only when there is absolutely no available data other that the total traffic volumes for all vehicles. In such case, total HazMat traffic are assumed to be a certain fixed percentage of the total vehicles traffic. Previous options are then carried out to estimate different HazMat traffic on links.

In this exercise we are estimating the different types of HazMat movements using truck AADT on links assuming HazMat movements constitute a certain percentage of all truck movements (option 3). The "Calculate HazMat Traffic Volumes from Truck AADT" window (Figure 5) asks for the percentage of HazMat movements in total truck traffic on links, β, and the "% of HazMat types in Total HazMat Traffic" window (Figure 6) asks for α^k value for different types of HazMat, *k*.

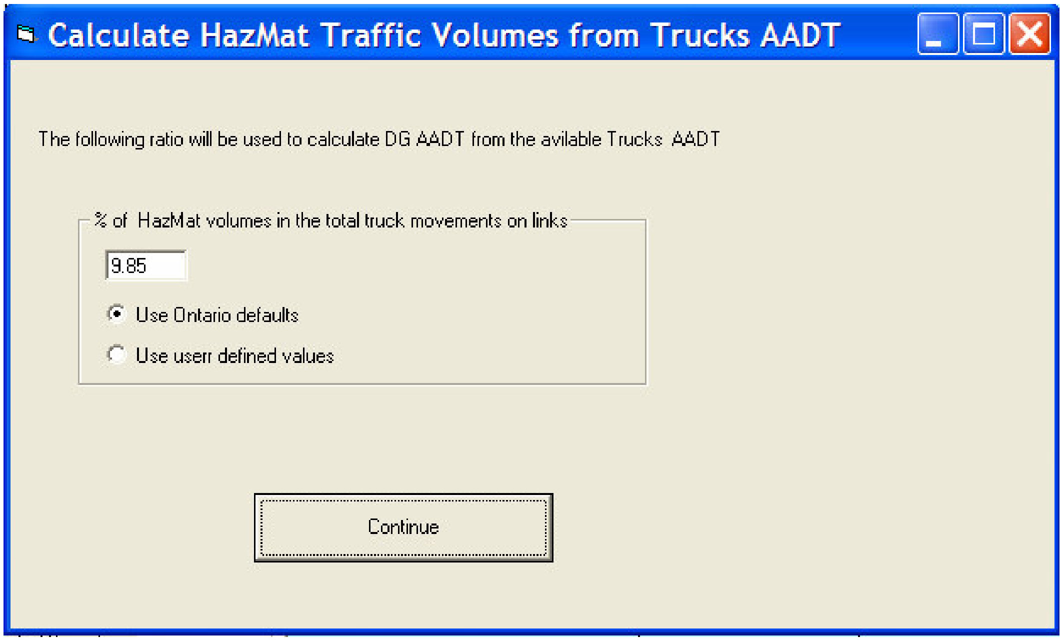


Figure 5: "Calculate HazMat Traffic Volumes from Truck AADT" window

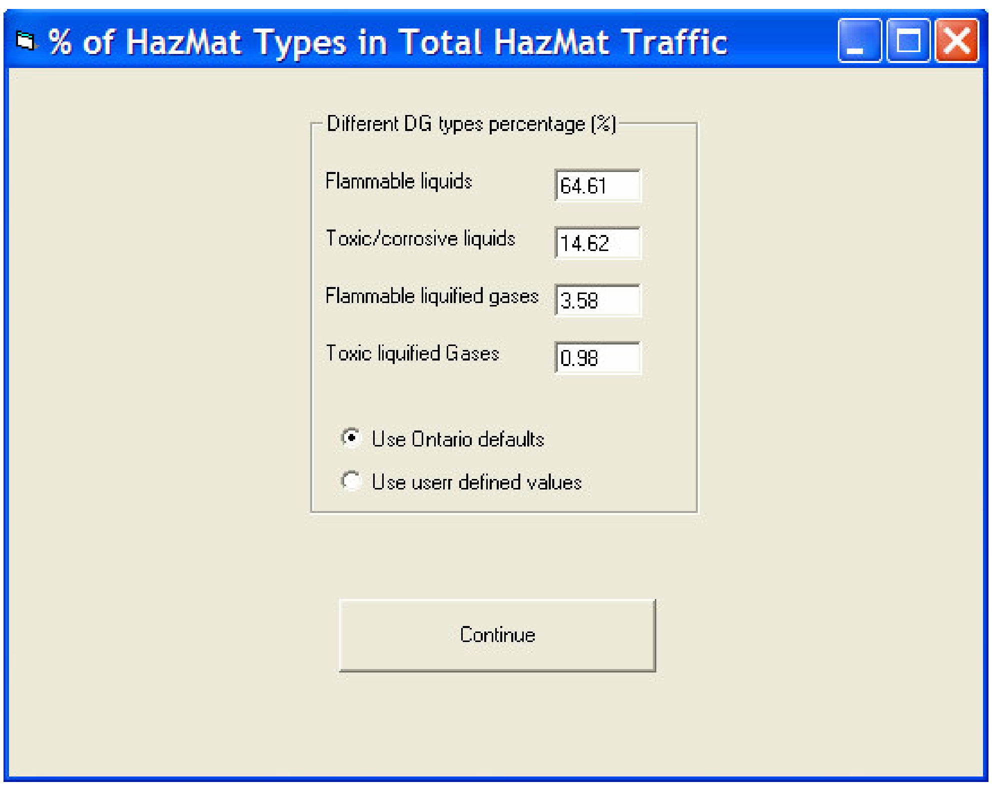


Figure 6: "% of HazMat types in Total HazMat Traffic" window

Accident and release rates

In the "HazMat accident rates" window (Figure 7), default values for accident rates on Ontario highways are provided. The next popup window is the "Release probabilities and discharge rates" window shows Ontario default values of release probabilities for different release scenarios (Figure 8).

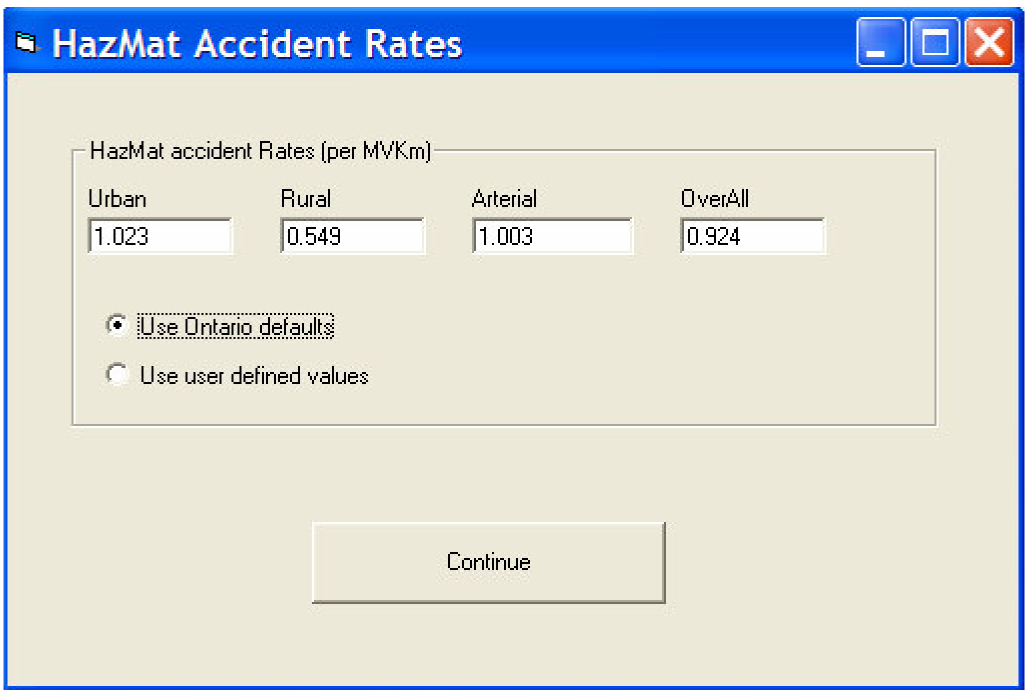


Figure 7: "HazMat Accident Rates" window

Using the provided input files and different run-time parameters, the HazMat-RiskLOM calculates risk estimates at different network nodes associated with different HazMat team candidate locations.

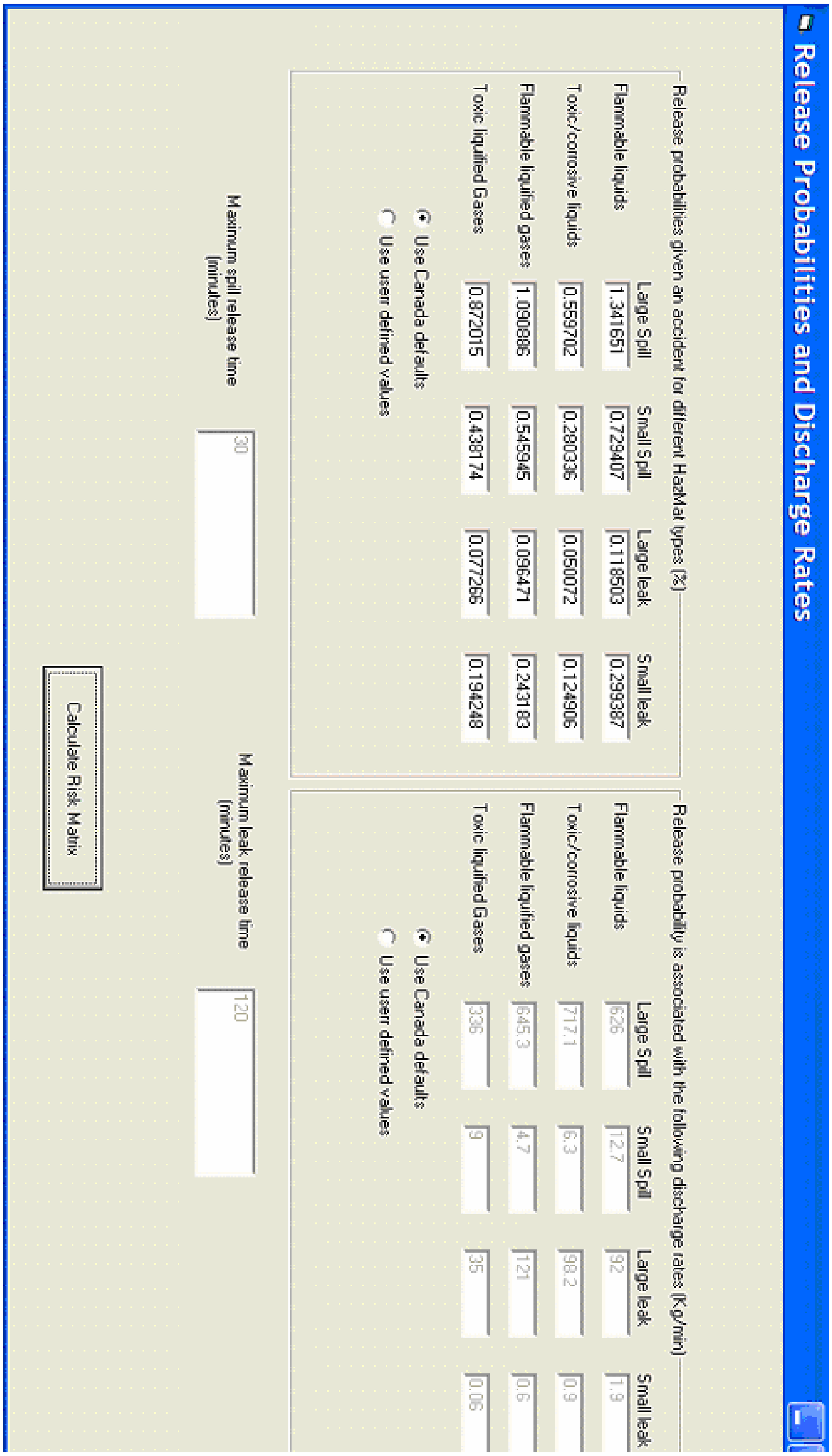


Figure 8: "Release probabilities and discharge rates' window

Assessing Specific HazMat Team Locations

The HazMat-RiskLOM could be used to assess the risk implications of a given HazMat team location solution. To sit HazMat teams at given locations select “Set HazMat team locations” from the “Network” menu. On the “Sit HazMat teams” window (Figure) select the node number at which you want to set a HazMat team and click the “Sit HazMat team” button. The node number will be added to the “HazMat team list” and you will be asked whether you want to sit another HazMat team or continue with calculations. When you finish siting all HazMat teams proceed with calculations.

The program calculates and displays total network risks, maximum risk, and maximum response time at marginal node for the specified HazMat team locations (Figure 9).

Locate HazMat Teams According to Minimizing Total Risk Criterion

To find the best total network risk minimization solution select “Find HazMat team risk minimization locations” from the ‘Network” menu. On the “Find Best Risk Minimization Solutions” window (Figure 10) determine the number of HazMat teams you would like to locate and the number of best solutions you want to view. You can either locate the HazMat teams to minimizes risk to humans or to minimize impact to the environment.

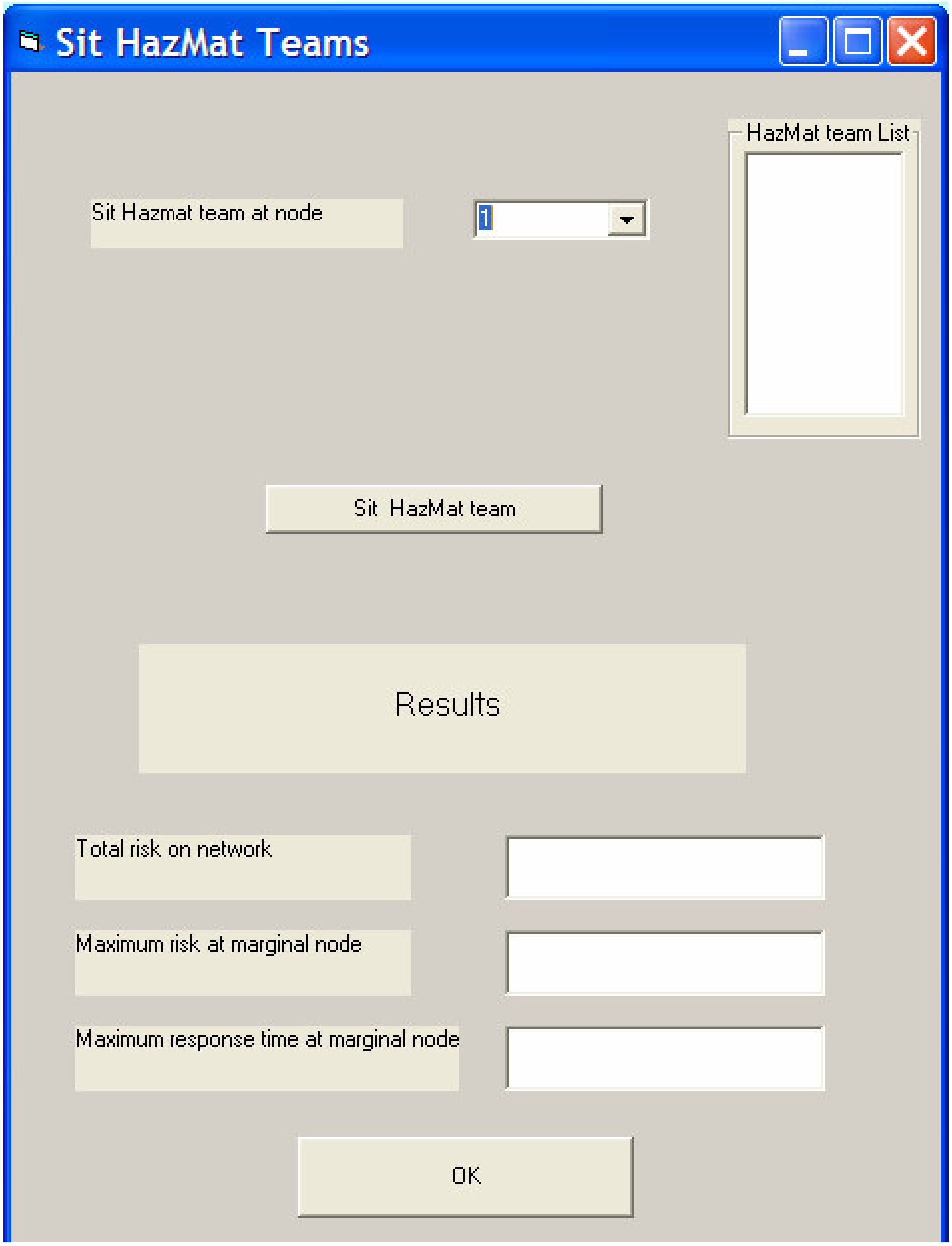


Figure 9: Siting HazMat teams at specific locations

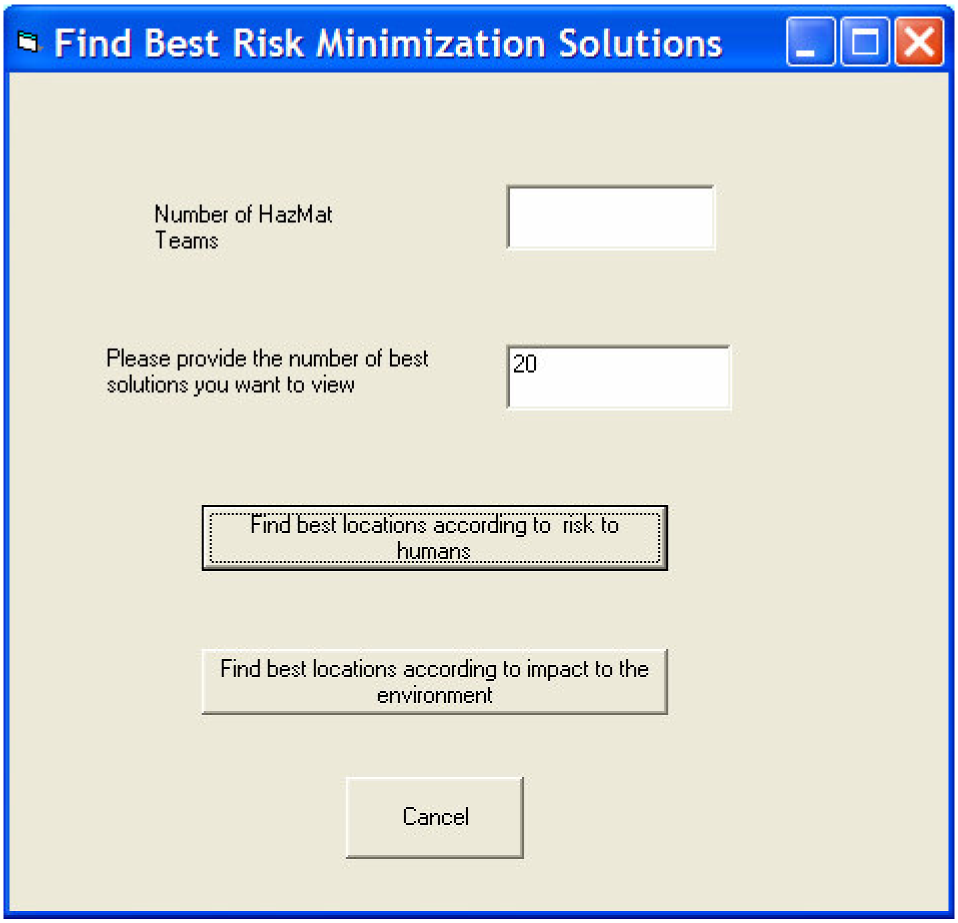


Figure 10: "Find Best Risk Minimization Solutions" window

Delete Network

The last item on the "Network" menu is the "Delete network" item. It allows you to completely delete the existing network to be able to input a new one.

EXAMPLE

In this example, part of southwestern Ontario region (shown in Figure 11) is used to illustrate the features and potential applications of the model. A simple network that consists of 32 nodes and 92 links is used.

Figure 11: Example southwestern Ontario area

Importing data

1) Start the program and choose the input options. In this example, the link length and posted speed are used to calculate travel time on links. HazMat traffic volumes are estimated using truck AADT.

2) Choose "Node data" from the "Import data" menu. Using the dialog box, navigate to open folder "2_3 Example linklength_trucks", then select and open the node file "Nodes long lat.txt". to import link data, select "Link data" from the "Import data" menu. From folder "2_3 Example linklength_trucks" open "Links_2_3.txt" file. Node attributes include: node id, longitude, latitude, population density, host fire station, urban or rural, and intersection and population center. Link attributes include: link id, head node, tale node, length, posted speed, truck AADT.

The model uses nodes and links information and displays a representation of the network (Figure 12). Nodes that host a fire station are represented by red circles, while other nodes are represented by black circles.

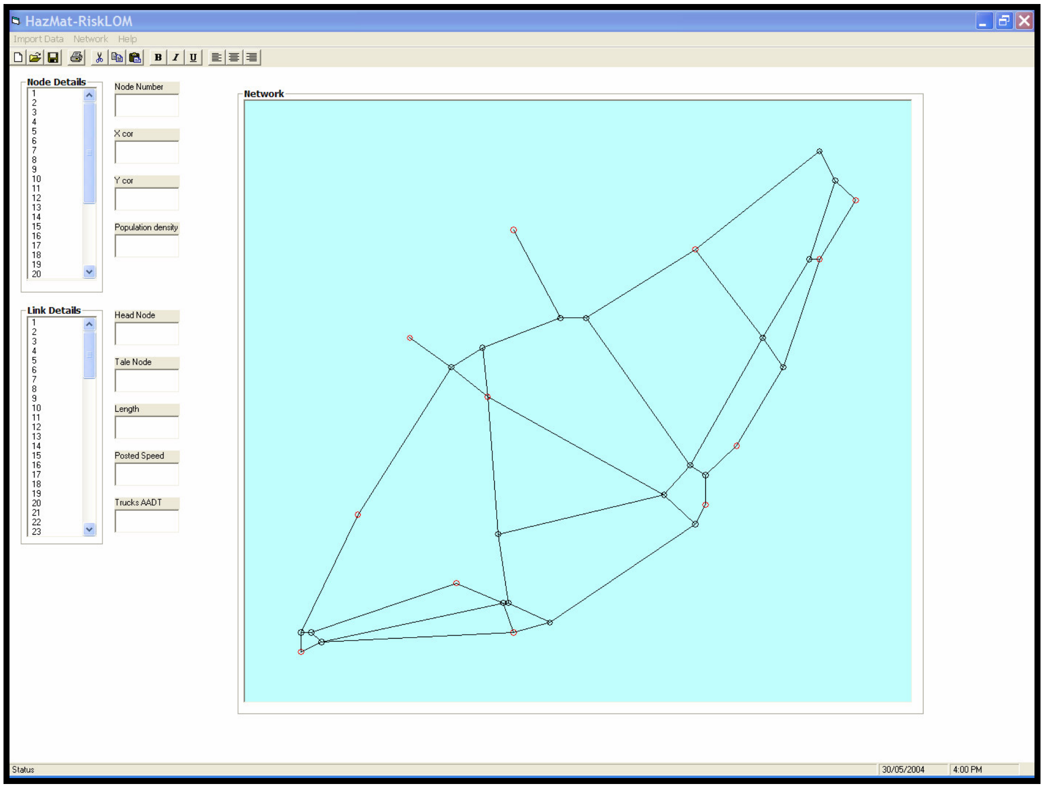


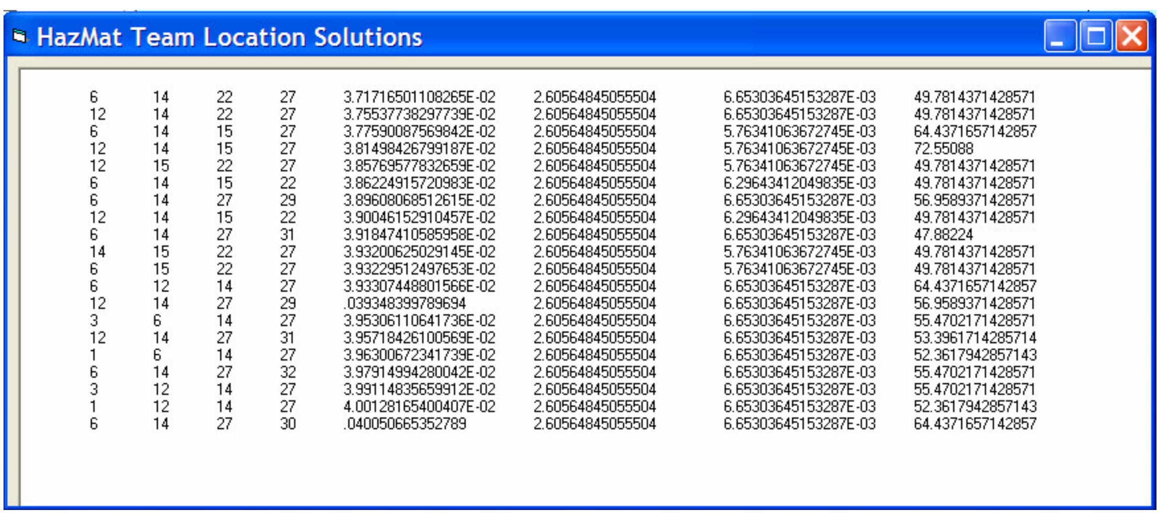
Figure 12: HazMat-RiskLOM example network representation

Response Times and Risk Calculations

1) From "Network" menu select "Calculate response time". Keep the default values in the "Response Time" popup window (Figure 4).
2) Select "Calculate risk" from "Network" menu to calculate risk for different node network. Several popup windows will be displayed with default input parameters values used in risk calculations. Follow the popup windows, keeping default input values. When risk calculations are complete you will be alerted with a notification massage.

Finding HazMat Teams Risk-Minimization Locations

1) Select "Find HazMat Team Risk Minimization Locations" from the "Network" menu.
2) Type "4" in the number of HazMat teams text box. Keep the number of best solutions to view at the default "20".
3) Click on "Find best locations according to risk to human" button.
4) The program calculate the best 20 human risk minimization HazMat location solutions and displays them in a text file (Figure 13). The first four values represent node numbers of HazMat team locations. The subsequent values represent total network risk, total frequency of release on network, maximum risk at marginal node, and maximum response time at marginal node respectively.


HazMat Team Location Solutions

6	14	22	27	3.71716501108265E-02	2.60564845055504	6.65303645153287E-03	49.7814371428571
12	14	22	27	3.75537738297739E-02	2.60564845055504	6.65303645153287E-03	49.7814371428571
6	14	15	27	3.77590087569842E-02	2.60564845055504	5.76341063672745E-03	64.4371657142857
12	14	15	27	3.81498426799187E-02	2.60564845055504	5.76341063672745E-03	72.55088
12	15	22	27	3.85769577832659E-02	2.60564845055504	5.76341063672745E-03	49.7814371428571
6	14	15	22	3.86224915720983E-02	2.60564845055504	6.29643412049835E-03	49.7814371428571
6	14	27	29	3.89608068512615E-02	2.60564845055504	6.65303645153287E-03	56.9589371428571
12	14	15	22	3.90046152910457E-02	2.60564845055504	6.29643412049835E-03	49.7814371428571
6	14	27	31	3.91847410585958E-02	2.60564845055504	6.65303645153287E-03	47.88224
14	15	22	27	3.932006250291145E-02	2.60564845055504	5.76341063672745E-03	49.7814371428571
6	15	22	27	3.93229512497653E-02	2.60564845055504	5.76341063672745E-03	49.7814371428571
6	12	14	27	3.93307448801566E-02	2.60564845055504	6.65303645153287E-03	64.4371657142857
12	14	27	29	.039348399789694	2.60564845055504	6.65303645153287E-03	56.9589371428571
3	6	14	27	3.95306110641736E-02	2.60564845055504	6.65303645153287E-03	55.4702171428571
12	14	27	31	3.95718426100569E-02	2.60564845055504	6.65303645153287E-03	53.3961714285714
1	6	14	27	3.963006723417394E-02	2.60564845055504	6.65303645153287E-03	52.3617942857143
6	14	27	32	3.97914994280042E-02	2.60564845055504	6.65303645153287E-03	55.4702171428571
3	12	14	27	3.99114835659912E-02	2.60564845055504	6.65303645153287E-03	55.4702171428571
1	12	14	27	4.00128165400407E-02	2.60564845055504	6.65303645153287E-03	52.3617942857143
6	14	27	30	.040050665352789	2.60564845055504	6.65303645153287E-03	64.4371657142857

Figure 13: Results for best 20 human risk minimization HazMat location solutions