A Simulation Study for Hazardous Materials Transportation Risk Assessment

Bhanu Prakash Rao Madala

A Thesis

in

The Department

of

Mechanical Engineering

Presented in Partial Fulfillment of the Requirements

for the Degree of Master of Applied Science at

Concordia University

Montréal, Québec, Canada

April 2000

0-612-47837-8

ABSTRACT

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All the areas in Canada are subjected to risk by hazardous-materials shipments. Some of these shipments take place locally or regionally, but a large number of them involve inter-provincial movements across significant distances, and this introduces further complications. According to a 1997 report of Transport Canada, roughly 56% of the total hazardous materials are transported by road annually from one state to another in Canada. Additionally, hazardous materials are transported via all major freight modes such as rail, marine and air.

There are several distinct interest groups essentially seeking the same goal — a reduction in the adverse effects of commercial transportation operation on the community. With this consensus position that transportation hazard analysis and incident management are important components of contemporary transportation operations and regulation, there is a need to develop methods and systems that can be used to assist decision makers in addressing these considerations. This research describes a methodology and system development that can be applied to this task.

This research presents a methodology for assessment of the hazardous material transport risk in a single commodity, multiple origin-destination setting. The province of Ontario is chosen as the study area and major cities are identified as points of origin and destination. Highway network in this area is the basis for identifying paths (routes) between origin-destination (cities) using different criteria such as distance, risk, etc. Gasoline shipments is chosen for the study.

We developed a simulation model in Visual Basic to assess the risk imposed on certain cities through which hazmats (Hazardous Materials) are being transported which also illustrates the number of people to be evacuated in case of an incident. The purpose of this research is to get a clearer understanding of hazardous materials transportation and describe a community's/region's hazardous materials transportation risk problem. The model developed also assists decision makers to develop the right policies to reduce the risk posed due to the shipment of hazardous materials to life and environment.

TO MY PARENTS ... Jhansi Lakshmi,Ram Mohan Rao

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation and thanks to my thesis supervisor, Dr. A. A Bulgak for his continuous support during all phases of this work. His care and encouregement has enabled me to achieve this educational step. Despite my endevour and all the generous support, this work would not have been the way it is, if not under the auspices, advise and motivation of Dr. V. Verter. He taught me and let me experience his principles of clear thinking, scientific thoroughness, and professional attitude. I would like to express my deep gratitude and respect for Dr. Verter. I would like to thank the faculty, staff and fellow students of the Mechanical Engineering Department at Concordia University, for their cooperation.

I want to thank the people from Statistics Canada, specially Jonathan Rose and Robert Lerocque for providing with the data needed for this research. I also want to thank my research associate Bahar Y. Kara for guiding me through out this work.

My thanks also goes to my roommates Bobby, Ravi and my friends Sahambi, Rama Raju, Jeet, Kiran and Prasad for their continuous encouragement through out this work. I would like to thank Mr. Achyut Rao and Mr. Danda Reddy for their valuable suggestions in building the code.

Last, but not least, I would like to dedicate this thesis to my parents for their love and encouragement to achieve excellence, without them this would not have been possible. I also wish to thank my sister Manju and Ramana Kumar for continuously pestering me to specify the date of my Master's graduation.

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Chapter 1

Introduction

1.1 Introduction

In industrialized countries a significant portion of the materials transported via highways, railroads, waterways, and pipelines can be extremely harmful to the environment and to the human health. Materials of this nature are called dangerous goods, or hazardous materials known as "HAZMATS"(HM). They include explosives, gases, flammable liquids and solids, oxidizing substances, poisonous and infectious substances, radioactive materials, corrosive substances and hazardous waste. Unfortunately, most hazmats are not used at their point of production, and they are transported over considerable distances. For example, from the data provided by Statistics Canada, it is estimated that 230 million tons of hazmats are transported annually across the Canadian highway, railroad, waterway and air. Out of this, 56 % of the transportation is through highways (Transport Canada Transportation of Dangerous Goods, 1997). According to HAIR (Hazardous Material Incident Report, U.S. D.O.T.,1983), mostly hazardous material are carried in bulk and 79 % of them are transported by cargo tanks which are custom-designed vehicles to prevent release of these materials into the environment in case of an accident.

Many governments allow dangerous goods movements only on designated roads, which avoid heavily populated areas. Nevertheless, accidental releases of the cargo to the environment do happen during transportation, which can have very undesirable consequences including fatalities and injuries. Thus, the residents along the roads used for hazmat transportation incur the risks of being exposed to toxic substances. For example, for a 90 tons rail car carrying chlorine [15], estimated an average rate of two fatalities and seven injuries per million kilometers of travel. Nevertheless, hazmat accidents do happen and in many cases have severe consequences, such as the 1979 train derailment in Mississagua, Ontario, where chlorine leakage from damaged tank cars forced the evacuation of 200,000 people. Hence it is necessary to designate routes for hazardous material transportation in which accidents damages are minimized. The hazardous materials are divided into nine classes in Canada and each class differs from another according to its physical, chemical, and hazard-related properties. A route that is safe for the transportation of one class of hazardous material may not be safe for the transportation of another as their hazard manifestations are different.

There are several distinct interest groups that have a stake in the reduction of hazardous-material transportation risk, both to the population and to environment. First, of course, is the general public. This group is becoming more concerned with environmental issues and is demanding attention to these issues. Another involved party is the government agencies run by elected and appointed officials, and charged with the responsibility of public safety. In an attempt to secure public and environmental safety, many governments have issued rules and regulations for hazmat transport. Common ways of regulating the dangerous goods transportation activity are :[43]:

1. Setting standards for the design of the vehicles to be used,
2. Designating the routs that can be used, and
3. Requiring the carrier companies to have insurance.

Also according to the United States committee of experts on the transport of dangerous goods the following principles should underline the regulations of the transport of the dangerous goods:

Transport of dangerous goods is regulated in order to prevent, as far as possible, accidents to persons or property and damage to the means of transport employed or to other goods. At the same time, the regulations must be framed so as not to impede the movement of such goods, other than those too dangerous to be accepted for transport. With this exception, the aim of regulations is to make transport feasible by eliminating risks or reducing them to a minimum. It is a matter therefore of safety no less than one of facilitating transport ("Transport", 1984). Finally, there is industry, providing the goods and services demanded by the public creating potential conflicts where economics and safety may be competing objectives.

Despite these perspectives, all three groups essentially are seeking the same goal - a reduction in the adverse effects of commercial transportation on the community. With this consensious position that transportation of hazard and incident management are important components of contemporary transportation operations and regulations, there is a need to develop methods and systems that can be used to assist decision makers in addressing these considerations. This research describes a methodology and system development that can be applied to this task. Transportation hazard involves complex procedures that are comprised of many individual components. These components and the difficulties that they introduce are discussed in this research as they relate to truck transportation.

1.2 Organization of the Thesis

Chapter 2 of this thesis outlines the literature review related to HM and the risk involved in their transportation. It describes several previous studies considered important for the present research.

Chapter 3 is a collection of flow data and accident case histories of the hazardous materials for provinces of Ontario and Quebec.

Chapter 4 deals with theory and concepts of risk assessment, shortest path and accident probability. Model formulation of the problem will be discussed in chapter 5. It defines the system concepts, routing based on risk, programming and database environments developed for the model.

Chapter 6 outlines the methodology adopted for our study and describes the goals accomplished after each phase of the methodology. The analysis of results and conclusions will be discussed in chapter 7. Finally we present some conclusions, suggestions and directions for future research in chapter 8.

Chapter 2

Literature Review

2.1 Literature Review

Performing risk and routing analysis can be a complex effort requiring a great deal of data, analytical capabilities, and co-ordination of several groups with often differing interests and agendas. One purpose of this research is to identify available commodity flow studies and databases used to analyze risk and highway routes in transporting hazardous material.

Several studies have been reported in literature on hazardous materials (HM) and wastes and the problems related to their movement on highway networks. These studies include database development, selecting criteria for designating HM highway routes, risk assessment of transporting HM, fatality rates and hazard areas for transporting HM by truck, truck accident rate model for HM routing, and methodology to determine safe routes for HM transportation. This chapter presents current literature relevant to the highway routing of hazardous materials shipment.

2.1.1 Database Development

A database is required to determine minimum paths for transporting different types of HM and predict the consequences of a possible accident. The database is generated by Geographical Information System (GIS). Burrough [27] has provided one of the most quoted definitions of GIS as "a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world". With the GIS, there is storage, management and integration of large amounts of spatially referenced data.

Abkowitz et al. [31], carried out a study on the use of GIS in managing HM shipments. They found that GIS is ideally suited for minimum path identification and risk computations, because it allows the integration of the transportation system with the environment. GIS mapping can integrate information such as geometric design elements, traffic flow conditions, accidents occurances on highway network with social and demographic factors, environmental, topographic and geological features to produce data on individual highway segments.

2.1.2 General Routing Issues

Routing issues are often based on the fact that local emergency response units do not feel equipped to respond appropriately to a potential incident. The political consequences of an incident improperly handled is something no local government wants to experience [18]. Past cases showed that state regulations conflicting with the Hazardous Material Transportation Act were held preempted because they focused too strongly on regional interests by increasing the total risk of the shipment [7]. Therefore, it has to be carefully considered with shipments need to be subjected to routing regulations as studied by Glickman [41]. In order to avoid the current cumbersome inconsistency routings and preemption processes, an efficient coordination between federal, provincial, and local legislation has to be determined [33]

[41]. For this purpose, federal regulation for the routing of non-radioactive materials should be broader in scope and less ambiguous in meaning [41].

Alternative safety approaches to regulations are based on procedures to select an optimal route for shipping a hazardous material from an origin to a destination. Urbanek and Barber [30] develop a methodology to determine criteria to designate routes for transporting hazardous materials. Several route factors were examined; e.g., traffic conditions (density, accident rate, speed variance, etc.), road conditions (width, pavement conditions, bad weather, etc.), and shipment conditions (quantity of hazardous materials, vehicle type, etc.). A panel ranking of accident causes showed the following rank: driver error, environment (weather, lighting), roadway design and characteristics, other motorist error, hazardous material vehicle performance. An additional ranking of road way characteristics put intersections at the top (most dangerous) and pavement surface at the bottom. Probabilistic models to determine the accident probability on a road were investigated and linear accident rate models are presented.

Hobeika et al. [19] presented an application of U.S DOT guidelines for selecting preferred routes for shipments of hazardous materials. They also discuss several modifications and additions to enhance their applicability to the route conditions under consideration. The traditional network problems in Hazardous Material Transportation (HMT) refer to strategic and planning purposes. Mathematical models for routing hazardous materials are generally based on single or multi-objective linear programming methods where the goal is to find an optimal route from an origin to a destination given a set of constraints.

Kessler [9] addresses the single objective problem of minimizing the risk sum on a network, where risk is defined as the product of accident probability and consequences. A mathematical formulation of the minimum risk problem is given below, where n is the set of nodes of the transportation network and r_{ij} the risk value of shipping a certain cargo from node i to node j. If a directed link between two nodes does not exist, the link-risk is assumed to be *infinity*. It is also assumed that the risk of shipping a cargo over several links is the sum of the link risks. The decision variables are the $x'_{ij}s$

$$\sum_{i=1}^{n} \sum_{j=1}^{n} r_{ij}\, x_{ij} \tag{2.1.1}$$

subject to

$$\sum_{j=1}^{n} X_{ij} - \sum_{k=1}^{n} X_{ki} = \left\{ \begin{array}{ll} 1 & i = \text{source} \\ 0 & \text{for all other i} \\ -1 & \text{for } i = \text{destination} \end{array} \right\} \tag{2.1.2}$$

$$x_{ij} \geq 0 \text{ for each } (i, j) \tag{2.1.3}$$

The objective function, Equation (2.1.1), minimizes the overall transportation risk from origin to destination. Equation (2.1.2) stands for flow conservation of the cargo; i.e., the vehicle leaves the source node, enters and leaves all the intermediate nodes along the route, and stops at the sink node.

Batta and Chiu [35] extended the idea of shortest path by assigning weights to the links, depending on the population neighborhood. The problem is to ship a vehicle containing hazardous material from an origin O to a destination D on a path p, where p is an element of P_{OD}. P_{OD} is the set of elementary paths between nodes O and D. The complexity of their objective function is due to the intricate definition of risk. The objective is to find a path p out of P_{OD} that minimizes the weighted sum of lengths over which the vehicle is "too close" to populated areas. The objective function to minimize is

$$\gamma(P) = \sum_{k \in N} W_k \sum_{(i,j) \in p} \int_{c=0}^{l(i,j)} \delta(k, c) dc + \sum_{(a,b \in A)} g_{(a,b)} \int_{z \in (a,b)} f_{(a,b)}(z) \sum_{(i,j) \in p} \int_{c=0}^{l(i,j)} \delta(z, c) dc dz \tag{2.1.4}$$

where w_k is a weight associated with each node, describing the undesirability of routing the vehicle near node k; e.g., w_K could be a measure of population intensity at node k; d(k,c) stands for a binary utility function; $g_{(i,j)}$ is a positive weight associated with each link; $f_{(i,j)}(Z)$ is a population density function associated with each link, and $l(i,j)$ is the link length.

Gilckman [38] studied rail flow patterns of hazardous materials using a national network model and generated alternative flow patterns representing population-avoidance re-routing policies. The study concluded that population exposure can be reduced by 25-50 % by re-routing at the cost of a 15-30 % increase in traffic circuity. He also formulated and applied a risk model which shows that extensive route changes can reduce casualities by about 50 %. However, extensive upgrading with or without re-routing can be even more effective.

Zografos and Davis [25] formulated a multi-objective model where the three objectives were to minimize disposal risks, routing risks, and travel time. List & Mirchandani reviewed the state of the art in HMT [22] [24] and presented an integrated network/planner multi-objective model for routing and siting hazardous materials and wastes. Their model aims to minimize:

- Transportation costs.
- Transportation risk as a risk equity consideration.
- The maximum level of risk per unit population for all the zones.

Saccomanno et al. [17] presented an interactive model for routing shipments of dangerous goods through an urban road network. The model computes minimum-risk routes based on each shipment's origin and destination, where risk is estimated considering accident rates, spill probability, spill impact area, and population exposed.

2.1.3 Risk Assessment

Risk is a measure of the possible undesirable consequences of a release of hazmats during their use, storage, transportation, or disposal. A release of hazmats can lead to a variety of incidents, for example, a spill, fire or an explosion in the case of flammable liquids, or a toxic cloud or plume in the case of pressure-liquified gases. As indicated by the examples in the previous section, the undesirable consequences of these incidents include fatalities, injuries, damages to property, losses in property values, and environmental damages. The release event can be caused by an accident, such as a core melt in a nuclear reactor or derailment of rail-car carrying hazmats. However, releases can also occur without an accident, such as leakages from a hazmat container, or toxic emissions from a hazardous waste incinerator. To differentiate between these two categories of risk, we call the former accident risk, where as the later constitutes espouser risk.

The most common measure of the societal risk associated with a potentially hazardous activity is its expected undesirable consequence. In other words, risk is usually defined as the probability of a release event during the activity, multiplied by the consequence of that event. This definition is appropriate only if a single release event is possible, such as a single shipment of hazmats between an origin and destination pair.

In the case of the multiple shipments, or the operation of a hazardous facility, the expected total consequence of all possible incidents needs to be computed. Thus, the major components of a risk assessment study are estimation of:

- The incident probabilities.
- The consequences of each incident.
- The volume of the activity.

The probability of an incident needs to be estimated per shipment, per unit distance, per unit time period, or per unit amount. Hazmat accidents are very rare events, which makes these estimation tasks nontrivial. The volume of the activity can be represented as the number of shipments to be made, the total distance to be traveled, the total time the hazardous facility would be operated, or the amount of hazardous waste to be processed.

Despite the fact that a variety of undesirable consequences are possible, most of the risk assessment literature focuses on fatalities due to the release of hazmats. Although, this approach simplifies the risk assessment process, its end result might be far from representing the absolute risk of a potentially hazardous activity. (An exception to this is the early work of Saccomanno and Chan [14] suggesting the assessment of dollar figures to fatalities and injuries). Even the estimation of the number of fatalities as a result of an incident, however, is quite difficult since for most hazmats the direct impact on human life is not well known. Fortunately, for many decisions in the strategic management of hazmats, usually a comparison of the relative risks of alternatives is needed rather than a quantification of the absolute risk of each alternative decision. It is however, crucial to be consistent in data collection and estimation in order to produce reliable assessments to the relative risks.

In a review of risk assessment methodologies for hazmat transportation, Abkowitz & Cheng [32] identified statistical inference as the most commonly used procedure for estimating risk. This technique presumes that sufficient historical data exists to determine the frequency and the consequences of the release incidents, and those past observations can adequately be used to infer future expectations. A number of studies have appeared in the literature identifying potential sources of information for hazmats risk assessment. In a series of papers List et al. [23], List and Abkowitz [20] and List and Abkowitz [21] reported on the major statistical sources in the U.S for gathering data on the movement of dangerous substances over the network of highways, rail roads and water ways. They focused on issues of completeness, consistency and compatibility both between and within the source databases commonly available.

Stough and Hoffman [36] focused on estimating the frequency of hazmat types on the highways of Indiana. Their results indicated that volume of the transportation activity was higher during the day and that flammable liquids and corrosives were the most frequent types of hazardous truck loads. Harwood et al. [47] presented analysis of data from several databases in the U.S to document the types of accidents and incidents that occur when transporting hazmats by truck. They identified traffic accidents as a major cause of severe hazmat incidents, and attempted to estimate the probability of a release given an accident. Using 1982 data, Glickman [40] provided estimates of release accident rates in the U.S in transporting hazmats by rail and truck. He concluded that there can be no general answer to the question of which mode is safer.

Harwood et al. [48] used weighted average of 1985-87 data from California, Illinois, and Michigan in estimating truck accident and release rates. Their study is of sufficient detail incorporating factors such as road way type, accident type, and demographic characteristics of the surrounding environment (i.e. urban vs rural). Glickman [42] presented an application of calculation of event probability in the assessment of the risks of highway transportation of flammable liquids in bulk. In a related study, Chow et al. [4] used Bayesian methods to estimate the chance of severe nuclear accidents and their risk. Apsimon and Wilson [28] however, suggested the use of numerical models in the assessment of the possible consequences of nuclear accidents. Once risk imposed on each individual due to hazmats is estimated using the techniques discussed above, a societal risk can be calculated as an aggregation of the individual risks. This societal risk in-turn, can be used as input for analytical models in hazmat logistics decisions.

Erkut and Verter [44] provided a frame work for quantitative risk assessment in hazardous materials transport. They first outlined a basic model where population centers are approximated by points on a plane with the assumption that in the case of an incident all residents in the population center will experience the same consequences. This model is valid if the hazardous materials route goes by small population areas. The extension of this basic model can be used to assess risks of shipping hazardous materials through large population centers that cannot be modeled as single points on a plane. In the extended model, large population centers are treated as two-dimensional objects on the plane, which allows for a more accurate treatment of consequences than the basic model. Assuming that each individual in a population center will incur the same risk, the societal risk can be expressed as a product of the individual risk and the population size.

$$R_{ipm} = IR_{ipm}POP_i \tag{2.1.5}$$

where,

IR_{ipm} = Individual risk at population center i due to the shipment of material m through path p

POP_i = Population at population center i

In general, a path between a given origin-destination pair can be represented as a set of road segments (indexed by s), where the road characteristics, such as accident rate and population density are uniform within each segment. Thus,

$$R_{ipm} = \sum_s P_s(A)P_{sm}(R|A)P_m(I|R)P_{ism}(D|I) \tag{2.1.6}$$

where,

$P_s(A)$ = Probability of an accident at road segment s per shipment

$P_{sm}(R|A)$ = Probability of the release of material m given an accident at road segment s

$P_m(I|R)$ = Probability of the incident, given the releases of material m

$P_{ism}(D|I)$ = Probability of death for an individual at population center i due to the material m incident at road segment

2.1.4 Fatality Rates and Hazard Areas for Transporting HM

The hazard area associated with each incident is affected by the type and volume of material released in each incident. Saccommanno et al. [15] performed a study on fatality rates and hazard areas for transporting chlorine and liquified petroleum gas (LPG) by truck. They considered instantaneous and continuous releases. For each type of release, three volume-rate classes were considered high, medium and low.

Given the spill size, various damage propagation models were used to establish the corresponding hazard area for different classes of damage. Two classes of fatality impact were considered -50 and 1 percent fatalities. The percentage in these criteria refer to the proportion of people killed within a given critical distance of each incident.

2.1.5 Truck Accident Rate Model for HM Routing

Estimates of accident and release rates are essential for conducting risk assessments in routing studies for highway transportation of HM. Glickman has shed light on the variations in release accidents rates by mode, carrier type, vehicle type and road/track classification. For example his estimates based on 1982 U.S. data, indicate that release accident rates of for-hire tank truck carriers was high. Saccomanno and Chan [14] used Canadian data to focus on the differences in truck accident rates (all accidents - not just hazardous material releases accidents) by time of day (day vs. night) and weather conditions (dry vs. wet). They found that the differences were highly dependent on roadway type. For example, on low-speed urban arterial, their estimate of the truck accident rate in wet conditions is less than the estimated rate in dry conditions, by a factor of two during the day and a factor of four at night. However, on expressway ramps, that relationship is reversed, with an estimated accident rate that is somewhat higher in wet conditions, and much higher at night than during daylight.

Harwood et al. [47] developed a truck accident rate model as a function of roadway type and area type (urban or rural) from state data on highway geometries, traffic volume, and accidents. California state data was used in his study. In determining truck accident rates, accident characteristics such as the number and types of vehicle involved, the type of collision, and the accident severity were important.

2.1.6 Methodology to Determine Safe Routes for HM Transportation

Given the extensive high way network of industralised countries, there may exist a very large number of routes for a given shipment. Hence, it may not be easy to select the preferred route by observation. However the selection of an "optimal" route, given a well defined objective, is conceptually a very simple task now to all students of operation research. Network optimization algorithms have existed in operation research, computing science and applied mathematics literatures for a long time [46]. Recent advances in hardware and software technologies allowed analysts to take these well known network optimization algorithms and implement them in user-friendly software packages to support solving practical decision problems. Large scale network optimization has been feasible for some time, and has been used in many industries with impressive results [13].

A methodology was developed by Astakala [1] for determining safe routes for the transportation of HM. This methodology is made up of four stages. In the first stage, a GIS database is developed. In the second stage, safe routes for population exposure or environmental component exposure are determined. Thirdly, consequences of one HM traffic accident on each link is determined by dispersion model which is specific for each type of HM. Finally, the probability of HM traffic accident for each type of HM is determined using traffic volume and accident record on each link. Accident probability multiplied by the consequences gives the amount of risk on each link. Erkut and Glickman [39] proposed a two-objective model, where the first objective was to minimize the travel time and the second objective was to minimize the maximum population placed at risk (catastrophe version). They suggested converting the second objective into a constraint, and finding travel time minimizing routes that do not go through road segments that have populations above a certain threshold.

2.1.7 Hazmat Transport Risks: Societal and Individual Perspectives

Risks associated with the transport of hazardous materials (hazmats) by truck and rail were viewed from two perspectives [16]: society in general and the individual residing adjacent to the route . Societal and individual risks assessed for the bulk transport of liquified chlorine gas along a typical highway/rail corridor (Sarnia-to-Toronto corridor in southwestern Ontario, Canada). The results of this analysis suggest that individual risks associated with the bulk transport of chlorine gas by truck and by rail are low, and in the acceptable range. Significant differences in individual risks were observed between the two modes. Societal risks are much more significant than individual risks, given their concern with very low frequency-high consequence events. For the bulk transport of chlorine along the selected corridor, societal risks for trucks are moderately higher than for rail. Consideration of both individual and societal risks renders the risk analysis process more complete for the purpose of decision making.

2.2 Case Studies

Actual experience in the process of designating minimum risk highway routes for hazardous materials transport is briefly described in the following case studies, which resulted from previous studies. These studies were selected because they were conducted in Canada and readily available for reference.

2.2.1 A Framework for Hazardous Material Transportation Risk Assessment

[44]

In September 1993, the Government of Alberta announced that ASWTC would be allowed to accept hazardous wastes from the Northwest Territories. The alternative for the Northwest Territories was to transport their hazardous wastes through Alberta to the U.S for treatment.

2.2.2 Minimizing Risk to the Population in the Transportation of Hazardous Material: A Routing for Shipments of Hydrogen Peroxide

[26]

Liquid hydrogen peroxide is shipped by truck from Maitland, Ontario to 42 destinations in the Northeast by Huron Services Group Ltd. Any accidental release of concentrated hydrogen peroxide presents a hazard due to the flammability and caustic nature of this oxidant. This study recommends a routing to eleven destinations in Quebec, a subset of all current shipments. Sections among routing alternatives are made in order to minimize risk to the population.

The paper offers a definition of the risk these shipments pose to the population and a method for estimating this risk numerically. The resulting risk values are applied to a linear programming model of the routing network. This model generates routes that minimize the numerical risk values between the origin and the required destination. A copy of the routes generated by this method will be given to the Huron Services Group who co-operated with the study by providing real-world examples of such shipments. The paper provides an example of a practical application of the concepts of hazardous materials transportation.

2.2.3 Minimum Risk Route Model for Hazardous Materials

[2]

The methodology used involves two major stages. In the first stage, alternative criteria to minimize population exposure units and environmental component exposure units are used to determine the routes between the origin-destination pairs, and are determined based on population risk units and environmental risk units minimization. Hazardous materials namely, Liquified Petroleum Gas, Sulphuric Acid and Chlorine Gas from three different classes are used. The concepts of normalization, criteria weighing and risk optimization are applied to determine routes between origin-destination pairs with a minimum amount of risk. A set of origin-destination pairs such as Sherbrooke-Quebec City, Montreal-Quebec City from the South Central part of Quebec Province are chosen to determine the minimum risk routes between them and to illustrate the concepts and methodology developed in this study.

Chapter 3

Data Collection

3.1 Introduction

With increasing traffic volumes of hazardous materials, concern over the safe transport of hazardous materials continues to grow. Government and industry alike see a need for safety and policy analysis to plan the minimum risk movement of these dangerous substances over the world's network of highways, railroads, waterways, and other transportation.

Flow data can be of a great value in this planning process. For example, the local governments can use the data to help set priorities for emergency preparedness training. Since response teams typically can not afford to be prepared for every conceivable emergency, flow data can tell them which types of substances they are most likely to encounter. This in turn can help direct training programs and equipment purchases. Also accident case histories concerning hazardous materials are an important source of (background) data for risk assessment. Obviously case histories contain extremely important information about what actually went wrong, rather than "what may go wrong", which is the normal result of a risk assessment.

Accident reports found in the literature or in databases will, however also reflect non-technical aspects such as the social and institutional context in which the report was drafted. To some extent the accident report may thus reflect the culture of the organization and the environment in which it is situated (e.g reflecting whether the origination is penalized as a result of the accident). At higher levels in the government, decision makers can use the data to weigh the benefits and cost of route control, roadside inspections, site-specific data gathering efforts, representative analysis of risks by mode, and other actions.

A typical accident case history appearing in an accident list will contain a number of data related to the accident, ranging from the date and the place to the chemical(s) involved. Often, however, important information may be lacking or incomplete.

3.2 Classification of Hazardous Materials

The legal definition of dangerous goods provided in the 1980 *Transportation of Dangerous Goods Act* as any product, substance, or organism included by its nature, or by the regulations in any of the nine classes listed in Schedule 2 of the regulation.

On the order of 3,500 products are listed in the *Transportation of Dangerous Goods Act*. Some have technical names such as chlor-tetra-fluoro-ethane; others have common names paint, petroleum and chlorine. Dangerous goods are divided into classes and divisions, according to the type of hazard involved. There are nine major categories as given in Table 3.1.

3.3 Hazardous Material Quantities and Transport

Statistics reported by the Transport Canada show that there were 27 million shipments transporting 230 million tons of hazardous materials last year in Canada.

Shipments of hazardous material are made by land, sea, and air (pipelines are excluded here). More than half of all the hazardous materials shipments (25 millions) are done by truck as shown in Figure 3.1.

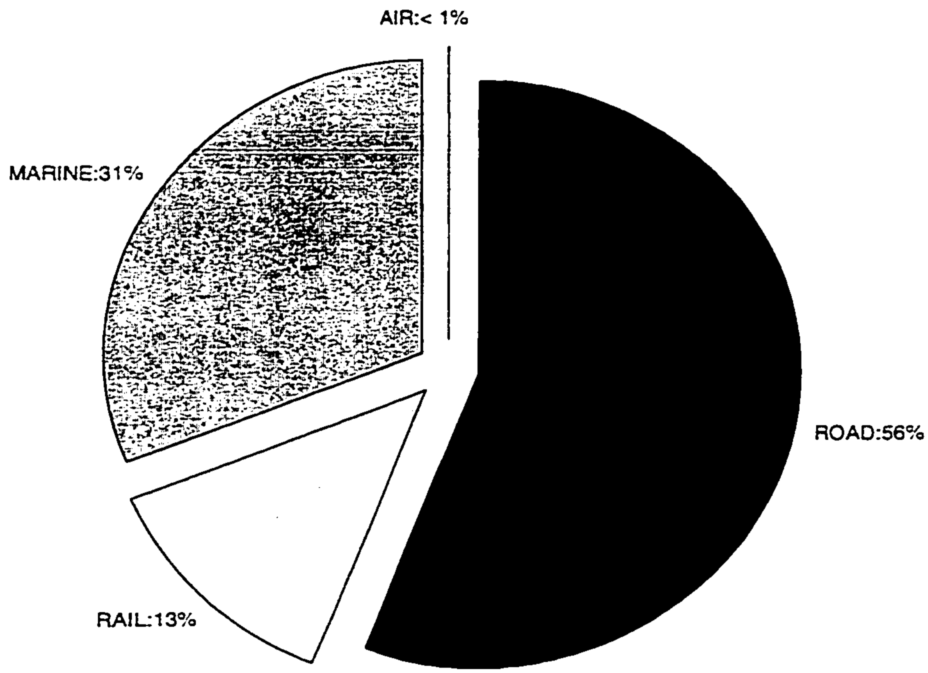

Figure 3.1: Dangerous Goods Tonnage estimates model share 1998

The vehicles used range from tank trucks, bulk cargo, carriers and other specially designed mobile containers to conventional tractor trailers and flat beds that carry packages, cylinders, drums and other small containers as given by OTA *Office of Technology Assessment, U.S.* [8]

Thirty million tons or 13% of hazardous materials were transported by rail last year, commonly in tank cars which have a working life of 30 to 40 years. Tank cars can be subdivided into pressure and non-pressure rail tank cars (for transporting both gases and liquids). Two thirds of the rail tonnage consists of chemical, and one fourth of petroleum products. The commodities most often shipped by rail are flammable liquids and corrosive materials (U.S. DOT hazard classes), each accounting for about 25% of the tonnage [8].

Last year 71 million tons or .31% of hazardous material was by marine transportation, which excludes bulk cargo. Transportation of hazardous material on inland waters is especially a problem for regions with an extended water network connecting large urban centers. Recent pollution of rivers in Europe by hazardous materials witness the acute threat of catastrophic events. This situation is particularly acute in the Rhine Valley in Europe, as evident from recent mishaps that resulted in pollution of the waterways. More than 90% of the tonnage in bulk marine transport consists of petroleum products and crude oil, typically involving very large quantities (millions of gallons).

The transport of hazardous material by air is performed either in all-cargo aircraft or in belly compartments of passenger aircraft. Roughly 92,000 tons or .04% of hazardous material were transported by air last year.

Substantive statistics on the quantity of dangerous goods produced or transported in the provinces of Ontario and Quebec are scarce. Much of what exists is derived from federal statistical or monitoring and regulatory agencies and is not necessarily compatible. Inferring from this data, on the order of 10 and 18 million tons of such goods are transported annually within the provinces of Quebec and Ontario respectively. Data from the Statistics Canada and Transport Canada suggest that the quantity of dangerous goods being moved has been increasing, commensurate with the economy. Commercial trucking tonnage of such products within Ontario and Quebec has increased by 60%.

In Ontario it is estimated that of the total 63% of the dangerous goods tonnage in the province, some 25 million tones are being hauled by trucks. The rail and the marine modes transport 23 and 14% of such tonnage, respectively, while the air mode handles about 1%, where as in the province of Quebec 13 million tones is hauled by trucks. While rail and marine contribute to 9 & 5% of the tonnage respectively, and the remaining 1% is transported by air. Transport Canada estimates that for the nation, trucks transport about 56% of all tonnage, compared to only 13% by rail.

Within the province, it is not known with certainty whether one mode is assuming greater importance in the overall movement of dangerous goods relative to another. However, a review of federal statistics on imports and exports of both the provinces suggests that the transportation of dangerous goods are increasingly being handled by trucks.

Although trends suggest a shift in modal share there is probably an upper limit to how much dangerous goods cargo can be hauled by trucks. For example, compressed bulk gases are now predominately, and more safely, transported great distances by rail. This assertion was partially, supported by the findings of 1988 analysis of U.S. DOT data, which concluded that, at least for rail tank cars and for-hire tank trucks (which tend to travel greater distance than there private trucks counterparts), the release accident rate for rail was lower than that of its principle long-distance competitor. However, preliminary information from the Canadian Ministry of Transportations 1988 Commercial Vehicle Survey suggests that even for commodities such as compressed gases, there is increasing use of trucks to haul it.

Dangerous goods are estimated as constituting approximately 68% of all trucks tonnage in Ontario. This amount is equivalent to just over 1 million truck loads a year or some 4,100 truck loads a day in the province. Where as in Quebec they amount to 17% of all trucks, which is equivalent to 1 million truck loads à year or 4,100 truck loads per day. But in many instances, dangerous goods form a small part of a larger general cargo movement- for example, a box of butane lighters as a part of a large shipment of goods being delivered to a convenience or a department store. Thus, the number of trucks that are actually hauling dangerous goods is much larger.

The principle commodity hauled by each mode varies. In terms of shipments, medicine is by far the most frequently transported dangerous good shipment by truck, followed by corrosive liquids, flammable liquids, paints and varnishes, and ethanol in that order. In terms of tonnage about 69% of the dangerous goods transported by truck is flammable liquids, such as gasoline, fuel oil or ethanol; the largest components of the remainder are fertilizers and corrosive liquids. In contrast, more than three quarters 74% of what is hauled by rail are compressed gases, flammable liquids and corrosives, they amount to 31%, 26% and 25% of the total hazardous materials respectively.

Of the majority of the truck movements carrying dangerous goods in Ontario, 28% are intra-provincial in nature, where as in Quebec they amount to 17%. In the Canadian Ministry of Transportations periodic commercial vehicle survey was found a greater amount of international movements of dangerous goods compared to such trips for all other commodities. Some 7% of dangerous goods truck movement were to the United States of America; consequently a higher proportion of truck traffic near border areas was related to dangerous goods. The value of trade in dangerous goods between Ontario and the United States was on the order of 5.6 billion.

Because of concerns about dangerous goods rail transport incidents, the federal goverment established Gilbert Task Force in 1986 to inquire about.

- The feasibility of rerouting or relocating rail traffic carrying dangerous goods in the Tornoto area and
- Any additional requirement governing the safe transportation of dangerous goods by rail.

From the information submitted by the task force, it was found that for long distance moves, generally more than 400 km in length, rail was the predominant means of transport for dangerous goods. For example, in contrast to the truck mode 42% of dangerous goods movements by rail in Ontario was interprovincial, whereas only one third was intraprovincial.

3.4 Issues and Concern

There are four principal issues or concerns related to dangerous goods:

- The safety levels of each transport mode;
- Risk minimization;
- Incident management adequacy; and
- Cost effectiveness of enforcement, regulation and movement restriction.

The objective of the federal and the provincial legislation is to protect the public. The regulation require safety marks and documentation enabling incidents to be dealt with safety and quickly. In addition, diligents enforcement ensures greater compliance with the regulations. Enforcement for on - highway activity is carried out by ministry enforcement officers and municipal police departments

The key areas of compliance are

- Proper and complete documentation.
- Appropriate safety marks(labels and placards), and
- Certificate of traning for the driver.

Much more work is still necessary in this area. For example, a major U.U. truck carrier manually audited every hazardous material freight bill for a week and found that 62% of its shipping customers was providing improper information or was in some way violating regulations. Highway enforcement is still the predominant means of ensuring compliance. Since 1985 in Ontario, the ministry and OPP (Ontario Province Police) have laid over 2,000 charges, and the courts have levied fines ranging from $100 to $2,000. In addition, occasional checks are made of the containers hauling dangerous goods by enforcement personnel. The experience of enforcement staff and the trucking industry is that the greatest risk of spills and the cited violations for the general freight carrier were in damage to or failure of drums and pails containing liquids.

3.5 Incident Experience

Although dangerous goods movement are frequent and accidents do occur from time to time, few accidents are significant enough to result in the release of dangerous goods, and fewer result in injuries or fatalities. The destruction of the James Snow overpass on Highway 401 near Milton in 1986 was the result of a dangerous goods incident that was initiated by a drunk driver. It was contained with the loss of only one life that occurred from the accident itself, not from the dangerous goods. The 1979 Mississauga derailment of toxic and chemical cargo despite the temporary evacuation of 240,000 persons, did not involve a single fatality.

For the most part, in the event of an incident, the type and amount of commodity transported would impact system operating personnel rather than the general public. Any harm would largely be contained within the immidiate right-of-way. However, the exposure may be relatively high in certain instances, and there may be a sufficient justification to rationalize the transportation network, in order to spread the risk.

According to Statistics Canada, in Canada, over 220 million tons of dangerous goods is moved over the nation's highway system annually. Between 1987 and 1998, the country has averaged about 416 incidents, 12 deaths, and 98 injuries/year. Within the major modes of transportation, roads contributed for the maximum number of accidents in transportation of dangerous goods. They account to 82% of the dangerous goods accidents. Railways account for another 11%, they are followed by air and marine with 1% and .39%, respectively, as shown in Figure 3.2.

From Figure 3.3 it can be noted that the number of accidents involving

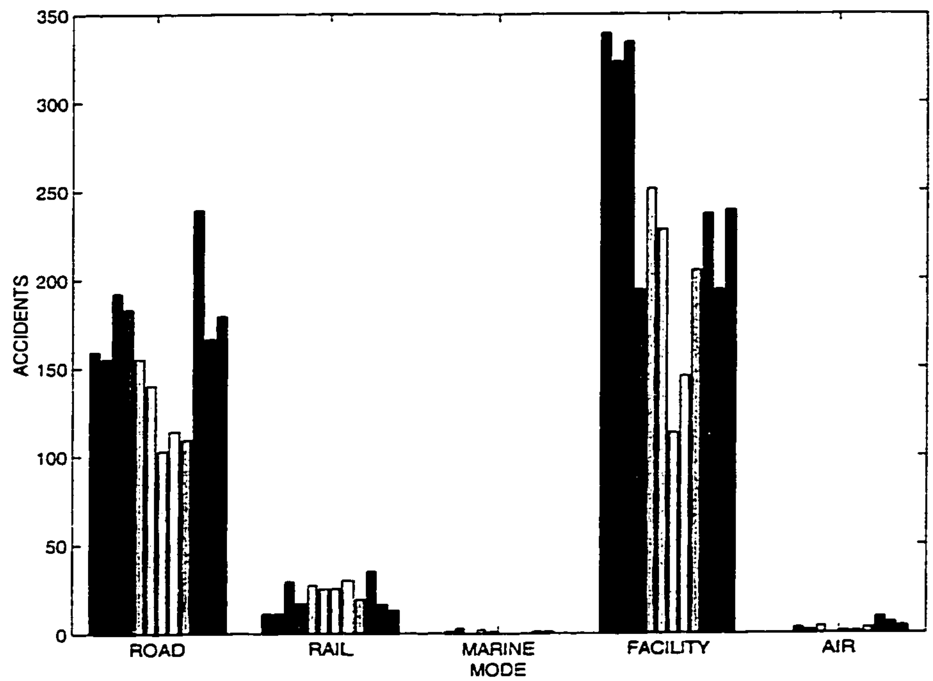

Figure 3.2: Dangerous goods accidents by Mode for Canada, 1987-1998

dangerous goods has increased nation wide as compared to last seven years.

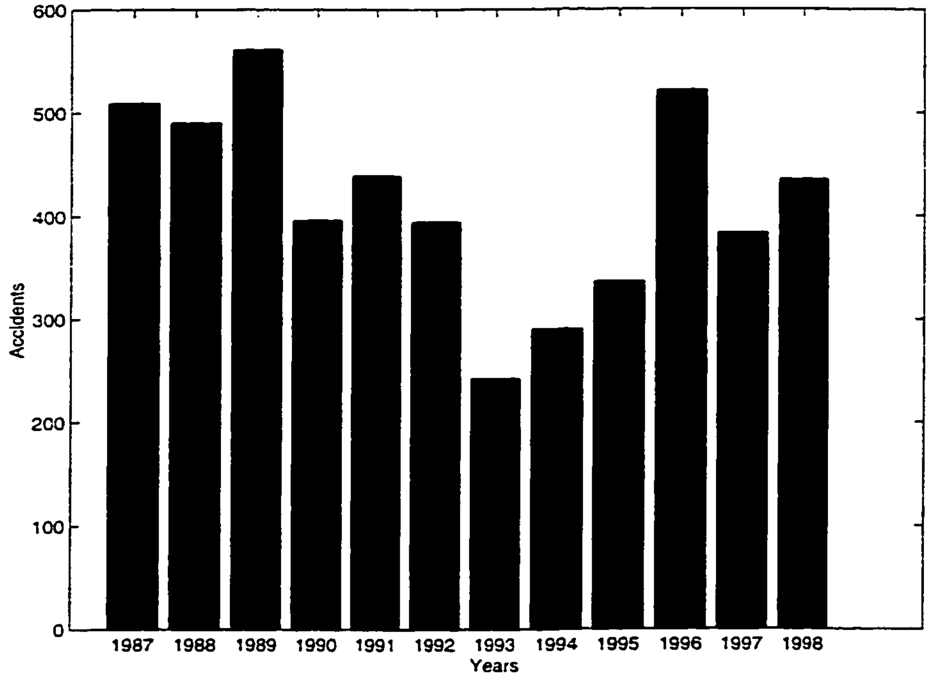

Figure 3.3: Total Dangerous goods accidents in Canada, 1987-1998

The highest proportion of dangerous goods accidents– just over one-third– occured in Alberta. Ontario which accounts for 21% of the accidents is the next most frequent location for dangerous goods accidents, followed by B.C and Quebec which account for 11% each as shown in Figure 3.4.

Alberta levels are higher because of the large volume of dangerous goods movement and the larger number of vechiles-miles traveled in the province.

Between 1987 and 1998, 170 persons were killed, average of 12 persons, annually in dangerous goods accidents in Canada.

Dangerous goods account for 88% of the total deaths. A total of 152 people were killed due to dangerous goods road accidents, which amounts to 88% of the deaths. Rail accidents caused 8 deaths and air accidents caused 3 deaths as shown in Figure 3.5. In the same period a total of 1170 people were injured, out of these

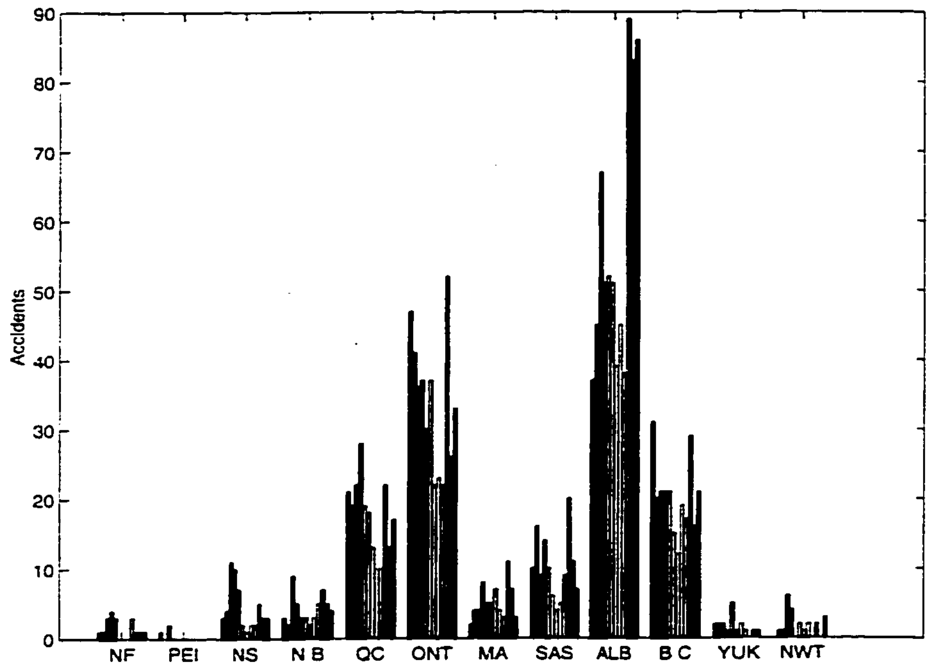

Figure 3.4: Total Dangerous goods Accidents by Province of Canada, 1987-1998

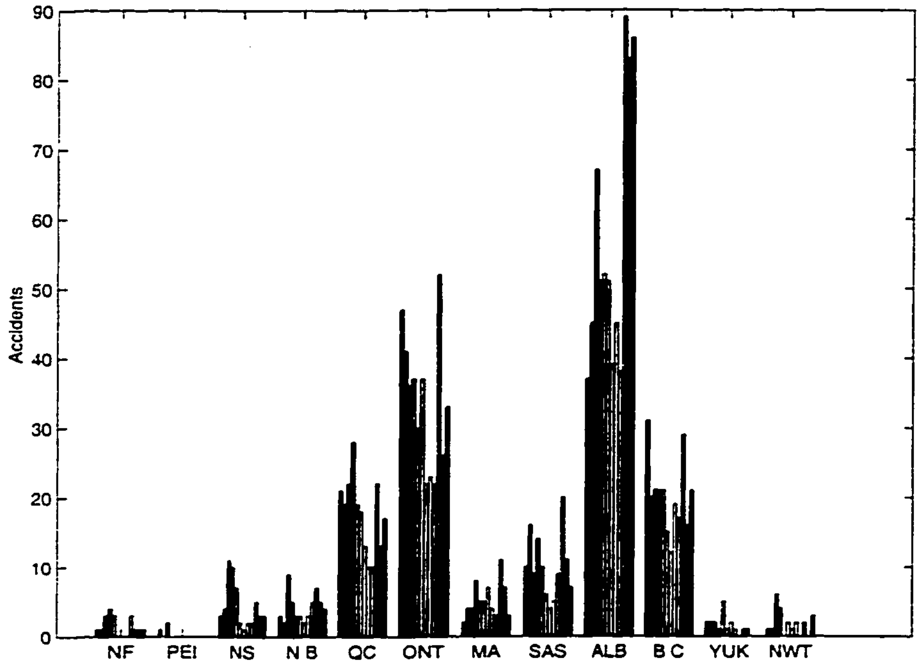

Figure 3.5: Total Number of Deaths due to Dangerous goods Accidents in Canada, 1987-1998

43% were major injuries as shown in Figure 3.6.

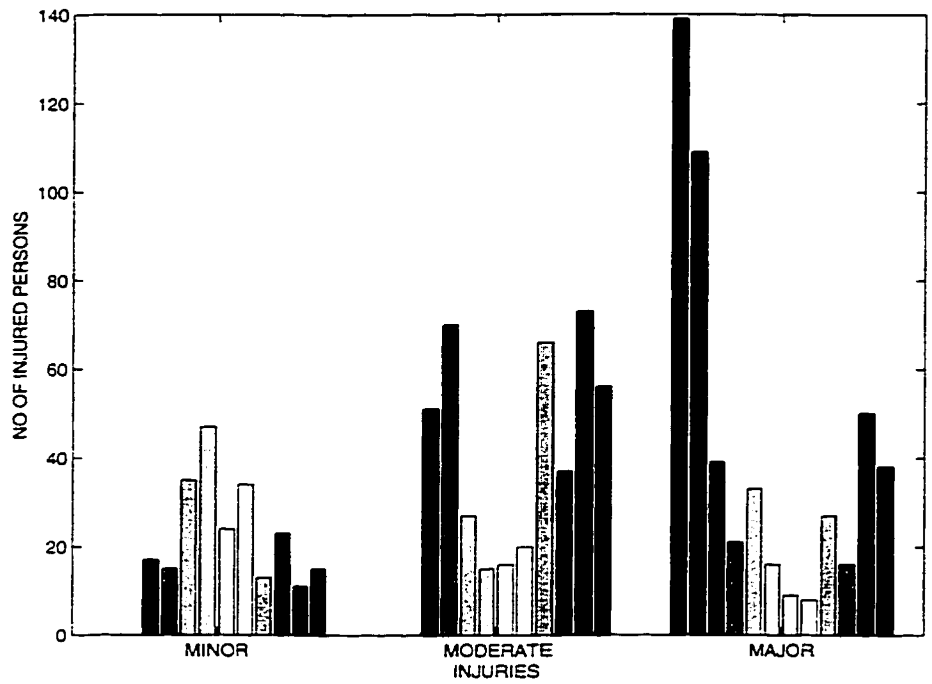

Figure 3.6: Total Number of Injuries Due to Dangerous goods Reportable Accidents, 1987-1998

A review of *Dangerous Goods Accident Information Systems* (DGAIS) from 1987 to 1998 for Canada provides the information that, 99 % of the road accidents occured during transit, 0.79 % of the accidents occured during handling and the remining due to storage as shown in Figure 3.7.

From Figure 3.8, about 55% of the road accidents caused spill and 19% of the accidents caused leak.

Out of 1170 injuries over the period of 12 years, 562 occured due to road accidents. One-half of the injuries could be directly attributed to the dangerous goods. Driver error was the most predominant reason for such a road transport related incident (68%), followed by Equipment and mechanical failure (10%); inclement weather was a more infrequent reason for the occurence of an incident (9%).

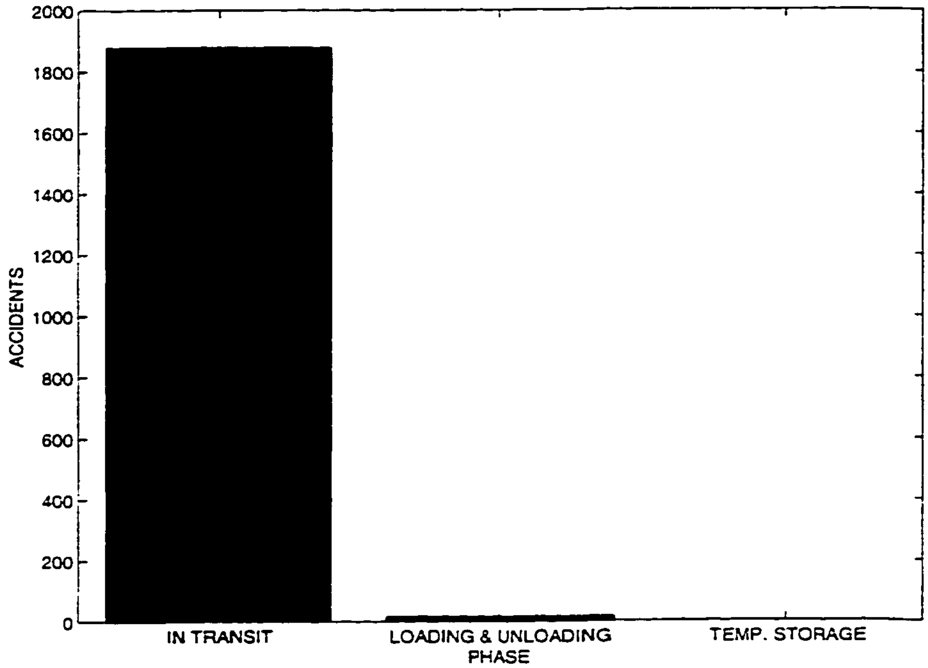

Figure 3.7: Dangerous goods Road Accidents by Phase for Canada, 1987-1998

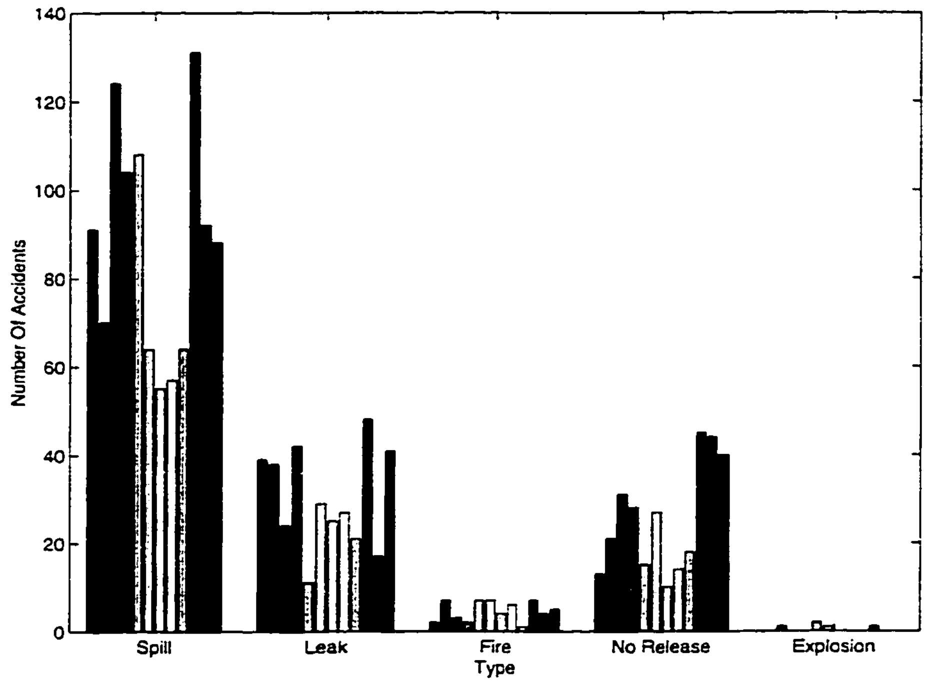

Figure 3.8: Accidents by Spill, Leak, Fire and Explosion

The total number of accidents between 1987 and 1998 recored in Ontario amount to 1308, resulting in 32 deaths. 31% of the accidents are due to dangerous goods road transportation. Railways accounted for 8% of the total accidents as shown in Figure 3.9.

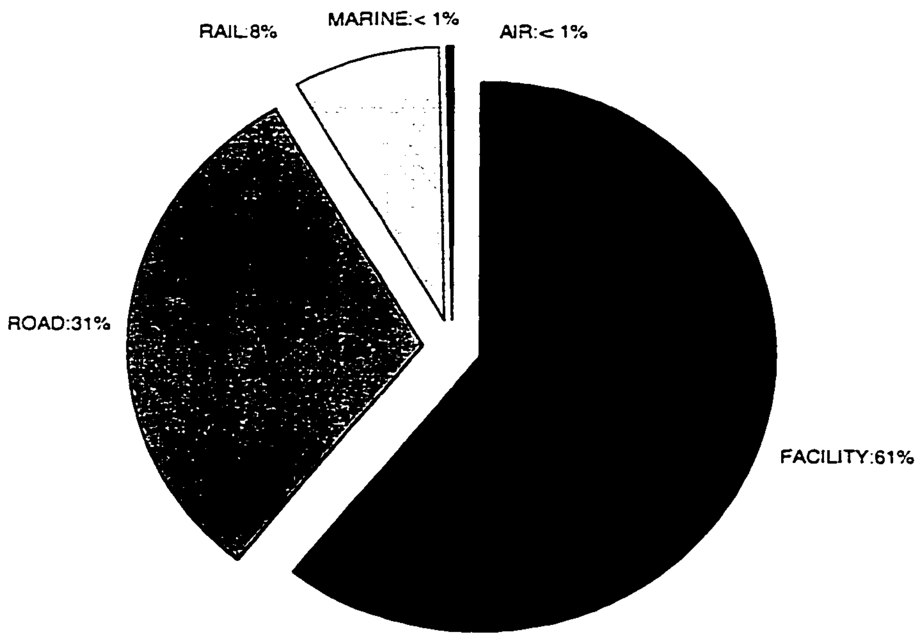

Figure 3.9: Dangerous Goods accidents in the province of Ontario for each mode 1987-1998

The maximum number of rail accidents occured in Ontario for this period. A total of 98 people were injured due to dangerous goods road accidents. 37% of the injuries were major ones. There was no discernible explanation for this spatial distribution.

In contrast, the number of accidents recorded in the province of Quebec for the same period are 570, resulting in 41 deaths. 37% of the accidents are due to tank trucks, 6% of the accidents are due to railways, 2% are due to marine and air ways contribute to .70% of the accidents as depicted in Figure 3.10. A total of 55 people were injured due to dangerous goods road accidents. 41% of the injuries were

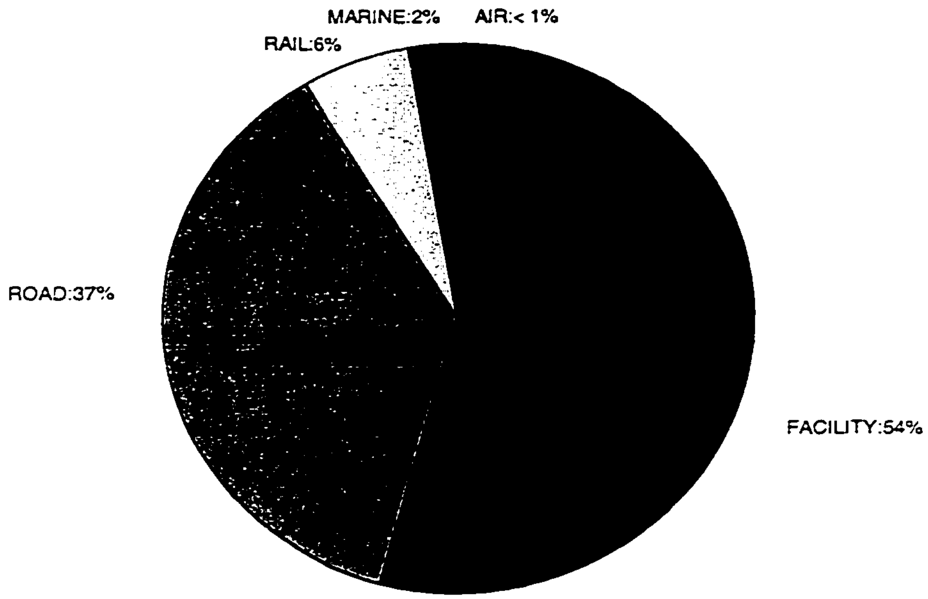

Figure 3.10: Dangerous Goods accidents in the province of Quebec for each mode 1987-1998

major.

Evidence conflicts as to what constitutes the safest mode for dangerous goods transport between cities. Theoretically, because the rail mode has its own right-of-way and can carry a larger quantity of such goods, the potential for an incident could be assumed to be less for this mode than for more frequent truck tavel required to carry the same volume of a commodity.

The potential for an incident to affect a larger area or population would be greater for the rail mode, given the larger volumes of goods involved. The 1988 U.S analysis also suggested that the estimated accident release rate for rail was in excess of that found for all trucks.

A cursory review of Transport Canada data would seem to support that conclusion simply on the basis of the number of accidents per ton transported . In 1998, the rail mode accounted for about 13% of the dangerous goods tonnage moved, resulting in 7% of the accidents related to dangerous goods amoung the various transport modes, while the truck/highway mode accounted for 56% of the tonnage moved and 91% of the accidents.

The subject of dangerous goods movement in the provinces of Quebec and Ontario is quite complex. Minimizing the risk to the public from occational incidents has been achived with regulations. Many groups have contributed to safety - shippers, carriers, and all levels of government. As such, the level of public risk is quite low, but further improvement is possible.

If decision makers are of the opinion that the existing risk level is still too high, alternative actions can be contemplated. These actions would have to be evaluated in terms of societal risk, community impacts, effects on the natural environment, and economic ramifications. Whatever, action is taken has to be achievable, effective, and enforceable.

Class 1	**Explosives**	**Examples**
Divisions 1.1	Explosives with a mass explosion hazard	Black powder
Divisions 1.2	Explosives with a projection hazard	Torpedo
Divisions 1.3	Explosives with predominantly a fire hazard	Fire works
Divisions 1.4	Explosives with no significant blast hazard	-
Divisions 1.5	Very intensive explosives	Blasting cap
Class 2	**Gases**	**Examples**
Division 2.1	Flammable gases	LPG
Division 2.2	Non-flammable gases	Chlorine
Division 2.3	Flammable gases	Ammonia
Division 2.4	Corrosive gases (Canadian)	sodium
Class 3	**Flammable Liquids**	**Examples**
Division 3.1	Flash point -18 C (0 F)	-
Division 3.2	Flash point -18 C and 23 C (73 F)	-
Division 3.2	Flash point -23 C and 61 C (141 F)	-
Class 4	**Flammable solids, spontaneously combustible materials, and Materials that are dangerous when wet**	**Examples**
Division 4.1	Flammable solids	Charcoal
Division 4.2	Spontaneously Combustible materials	-
Division 4.3	Materials that are dangerous when wet	-
Class 5	**Oxidizers and Organic Per-oxides**	**Examples**
Division 5.1	Oxidizers	Chromid acid
Division 5.2	Organic Per-oxides	Benzoyl peroxide
Class 6	**Poisonous and Etiologic (infectious) materials**	**Examples**
Division 6.1	Poisonous Materials	Hydrocyanic acid
Division 6.2	Etiologic (infectious) materials	Polio Virus
Class 7	**Radioactive Materials**	**Uranium**
Class 8	**Corrosives**	**Soda Lime**
Class 9	**Miscellaneous hazardous materials**	**Wastes**

Table 3.1: Classification of Hazardous Materials

Chapter 4

Risk Assessment

4.1 Definitions and Approaches in Risk Assessment

Risk is most commonly defined as a combination of the probability of an abnormal event or failure and the consequence of that event or failure to a system's operators, users, or its environment [12]. The consequences considered range in seriousness all the way from "no concern" to "catastrophe". From this definition, other well known notions in risk management can be derived. Hazard presents therefore only part of risk. i.e., the potential for injury, death, or any other perceived danger. Reliability is a measure for a system's proper performance over a certain time. Risk Assessment is defined as the processes and procedures of identifying, characterizing, quantifying evaluating risks and their significance [12].

These definitions are not unique in the risk management community. Risk is defined as the expected number of fatalities, without referring explicitly to probabilities, or as the probability of a hazard, without describing its consequences. Mandl and Lathrop [5] refer to several definitions of risk introduced by Keeney et al. [29]

such as societal risk (total expected fatalities per year), group risk (annual probability of death of an individual in a group), or individual risk (annual probability of death of an exposed individual). Risk assessment, risk and risk evaluation are also defined in several ways.

In the context of hazardous materials, risk is a measure of the possible undesirable consequences of a release of hazmat during their use, storage, transport, or disposal. A release of hazmats can lead to a variety of incidents, for example a spill, a fire or an explosion in case of flammable liquids, or a toxic cloud or plume in the case of pressure-liquified gases. The undesirable consequences of these incidents include fatalities, injuries, damages to property, losses in property values, and environmental damages.

The release event can be caused by an accident, such as core melt in a nuclear reactor or derailment of a rail-car carrying hazmats. However, releases can also occur without an accident, such as leakages from hazmats container, or toxic emissions from a hazardous waste incinerator. To differenciate between these two categories of risk, we call the former accident risk, the later constitutes exposure risk.

4.1.1 Risk Components

The estimation of risk is based on three constituent components:

Probability Includes the occurance of an undesirable event (e.g., a train derailment or truck accident involving dangerous goods), and the condition that this event will result in a release of hazardous material for different release rates and volumes.

Consequence The consequences of these releases depend on the hazard areas associated with each likely release profile, and on the number of people affected for different classes of damage (eg., fatalities, personal injuries, property damage).

The volume of the activity The volume of the activity can be represented as the number of shipments to be made, the total distance to be traveled, the total time the hazardous facility would be operated, or the amount of hazardous waste to be processed.

Factors that affect the extent and likelihood of accident-induced releases depend on the physical properties of the truck tanker containment system and the operating speed of the vehicle at the time of the accident. The release mode (nature of components released) affects both the rate and volume of the material included in each spill. Control factors on the consequent damages (e.g., number of fatalities) include the spill environment, material properties and the distribution of population in the vicinity of each incident.

Various hazard areas can be determined for each damage level under consideration. Each of these areas has an associated term for the probability of occurrence, which is based on the accidents/release likelihoods for different release volumes and rates.

4.2 Shortest Path Concept

A path is the route or direction to follow from a point of origin (O) to a point of destination (D). A path is made up of links which are segments of the route. These links have some characteristics or attributes which are known as link impedence. Link attributes are defined in terms of distance, population exposure, environmental component exposure and risk. The shortest path is a path with the minimum amount of a specific impedence between the O-D pair *Origin - Destination.*

A shortest path between a given O-D pair using a specific impedence, for example, distance, gives a route that has a minimum distance between the O-D pair. Similarly, using population exposure units as link impedence, gives a route that has the minimum number of people exposed to it.

4.3 Accident Probability

The probability of a HM *Hazardous Materials* accident is computed from the following equation:

$$P(A)_i = AR_i * L_i \tag{4.3.1}$$

where,

$P(A)_i$ = Probability of a HM accident for route segment i.

AR_i = Accident rate per vehicle-mile for all vehicle types on route segment i

L_i = Length of route segment i.

The availability of truck accident rates and release probabilities, permits the estimation of the probability of a HM accident in which a release occurs. The probability of a releasing accident is computed using the following equation which replaces the above equation:

$$P(R)_i = TAR_i * P(R/A)_i * L_i \tag{4.3.2}$$

where,

$P(R)_i$= Probability of an accident involving a HM release for route segment i.

TAR_i = Truck accident rate (accidents per vehicle-mile for route segement i)

$P(R/A)_i$ = Probability of a HM release given an accident involving a HM truck for route segment i

L_i = Length (miles) of route segment i

The above equation is more appropriate for HM routing analysis than the latter equation because :

1. Risk is based on the probability of a HM release rather just on the probability of an accident, and
2. Risk is based on truck accident rates rather than all vehicle accident rates.

The above equation retains the proportionality of risk to route segment length, which is central to all routing analysis. Truck accident rates have not yet been established for highways in Ontario. Default values from studies in California for truck accident rates, release probabilities given an accident for different roadway type and area type were used in this study. These values are presented in Table A.6 of Appendix A

4.4 Risk Assessment

In designating routes for hazmats transport, it is crucial to be able to compare the risks of alternative decisions. This requires quantification of risk associated with the various transportation, storage and disposal options for hazmats. Several risk assessment methodologies are available for this task. The risk posed by a shipment of hazardous material can be defined as [11] [45]:

Event Risk = (probability of the event)* (the consequences)

This definition is appropriate only if a single release event is possible such as a single shipment of hazmats between an origin and destination pair. In case of multiple shipments, the expected total consequence of all possible incidents needs to be computed. The equation above can be modified to reflect the societal risk posed by repeated shipments by including the required number of shipments as a multiplicative factor.

Abkowitz and Cheng [32] in their survey of methods provide an analytical approach and a Bayesian analysis. They state that a typical analytical approach is to assume that spills are independent events that occur randomly;

$$P(n) = [(vL)^n/n!]e^{-vL} \tag{4.4.1}$$

where,

n = Number of spills (a discrete random variable, poisson distributed with parameter

vL if the independence assumption is met).
L = Distance .
v = The average number of spills per mile.

Bayesian analysis provides a way to incorporate information relating to the same event but derived from different sources, such as expert opinion and historical data [32]. The objective is to get a better result than would be obtained by using the limited historical data or the expert opinion alone. From Bayes theorem we get;

$$p(A|B) = p(A)[p(B|A)/p(B)] \qquad (4.4.2)$$

where,
A and B represent information relating to the same event derived from different sources,
$p(A)$ = the prior probability
$p(A|B)$ = the probability that Effect B was caused by Event A
Risk to the population R, is here defined as

$$R = POP * \sum P(A)P(R|A) \qquad (4.4.3)$$

where,
$P(A)$ = Historical probability of accidents per km for a given type of road, summed over the length of the road segment
$P(R|A)$ = A historical percentage of accidents that resulted in a release
POP = Resident population within the neighborhood of the road. The explanation of POP follows:

Glickman [42] argues that using historical records can simulate the probability of an event. The expected consequences per unit volume of activity are expressed by,

$$C_s = \sum_x P(X)C(X) \qquad (4.4.4)$$

where,

C_s = Expected consequences of activity on segment

$P(X)$ = The probabilities of each of the possible outcomes of X

$C(X)$ = Corresponding consequences

If an adverse outcome X is conditional on a release R, conditional on accident A is given by equation:

$$P(X) = P(A)P(R|A)P(X|A, R) \tag{4.4.5}$$

where,

$P(A)$ = A historical rate of accidents per truck mile for the given operating conditions per segment-mile.

$P(R|A)$ = A historical percentage of accidents that resulted in a release.

$P(X|A, R)$ = A historical percentage of release accidents with adverse outcome X.

$C(X)$ = The consequence of X.

Saccomanno and Chan [14] include stochastic and deterministic influences in their risk definition;

$$R_i(k) = \sum_j P_{ij} * D(k) \tag{4.4.6}$$

where,

$R_i(k)$ = Objective risk on a unit interval of class i road,

P_{ij} = Joint probability of accident occurrence on road class i for stochastic event j (accident due to the joint probability of the deterministic and stochastic factor)

$D(k)$ = Likely damage associated with link k of the road network.

4.5 Population Exposure

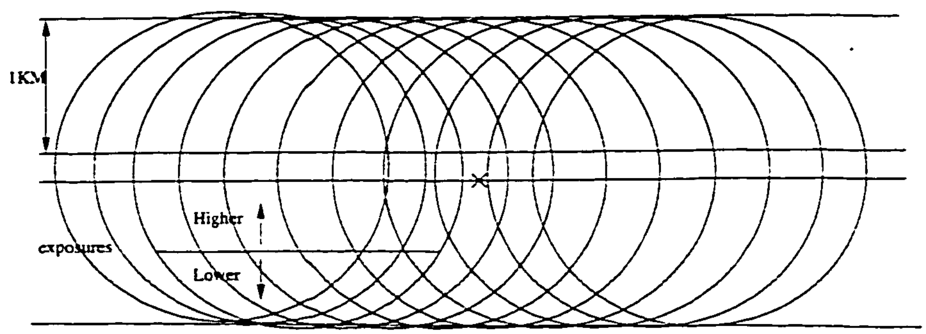

Figure 4.1: A section of highway with uniform surrounding population density

Consider the hazard posed by an event X, a serious accident involving a truckload of hydrogen peroxide. Since the truck moves along the highway, an accident could occur anywhere along this corridor, there is an infinite series of possible sources of hazard. As the partial series of circles shows, people closer to the road are exposed to more possible hazard sources than those who are nearly 1 km away from the road.

Another way to conceptualize this is to imagine a person standing beside the road. This person will be within 1 km of a passing truck from the time the truck is 1 km away on approach until the truck is 1 km away after passing by. The time of exposure would be 1 minute 12 seconds if the truck travels at 100 km/hr. A person standing 1 km away from the road will only be within 1 Km of the passing truck for a fraction of a second.

Batta and Chiu (1988) [35] refer to the total area of exposure as the λ neighborhood where λ = the radius of hazard. Note the additional exposure areas beyond the terminals of the line segment

Given the importance of proximity to the hazard, it is worthwhile to examine population densities near proposed routes carefully. Alp (1995) [11] models societal risk S based on the probability P of individual consequences e due to event h as

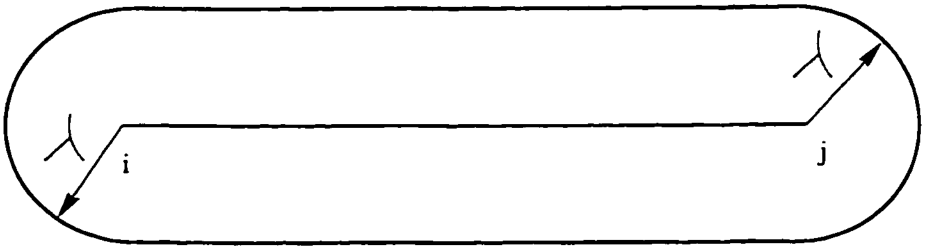

Figure 4.2: Exposure from road segment i-j the λ neighborhood

$$S_{e,h} = \int\int\int P_{e,h}(x, y, z, x', y', z')\rho(x, y, z,)dxdydz \qquad (4.5.1)$$

where (x, y, z) are points in three-dimensional space exposed to the hazard from a risk located at (x', y', z') and $\rho(x, y, z)$ is the population density. Alp's model is the most comprehensive in accounting for consequences of a hazardous incident as it incorporates thermal radiation, blast waves and dispersion of toxins etc. from whatever is known about the properties of the material being studied. This paper does not distinguish between the various eventualities which would merely be sub divisions of the "conditional release probability" shown later.

Erkut and Verter [44] presented a model, which considers the distance of each individual from the hazard source. Their model assumes that risk declines in a linear fashion with distance from the source. In the first model called basic model, where population centers are approximated by points on a plane with the assumption that in the case of an incident all residents in a population center will experience the same consequences. This model will be valid if the hazardous materials route goes through small population centers. The societal risk at population center i as a result of this transportation activity can be represented as follows:

$$R_{ipm} = IR_{ipm}(POP_i)N_{pm} \qquad (4.5.2)$$

where,

IR_{ipm} = Risk imposed on a individual at population center i due to a single shipment.

POP_i = Number of people living at population center i.

N_{pm} = Number of shipments of hazardous material m on path p.

The extension of the basic model is used to assess risks of shipping hazardous materials through large population centers that cannot be modeled as single points on a plane. In the extended model, large population centers are treated as two dimensional objects on the plane, which allows for a more accurate treatment of consequences than the basic model. Societal risk at population center "i " is given as:

$$R_{ism} = P_{sm}(I)(POP_i)\lambda_m(\pi/2) \tag{4.5.3}$$

where,

P_{sm} = The probability of an incident on segment s

m = A material m incident

I = Population center

POP_i = The number of people in the impact area

λ_m= Radius of hazard

The method proposed here is to consider resident population density by census subdivisions using the figures from the 1991 census. This method uses night or resident population. They also suggested that the study should be expanded to include day population. The location of people at work and at school or at evening entertainment would increase the validity of the modeling only if the shipments could be scheduled to profit from this information. It is beyond the scope of this study to measure day time populations or recommend the hour at which trucks should leave the plant. Still, night populations are of interest since much of the trucking of hazardous materials is done during the night with many trucks leaving after midnight.

4.6 Exposure Radius

The most hazardous releases would be from ruptured containers due to collisions or nuclear waste exposure during transportation. The expected radius of hazard is obviously an important estimation that will dictate the number of people exposed due to the use of a given road. Chin and Cheng [37] found that different radie of hazard could generate different risk-minimizing routes.

The workbook for Canadian municipalities prepared by LaMorte-Williams & Associates (1987) also recommends a 1 km distance on each side of a roadway as an exposure zone for all hazardous materials. Pijawka et al. [10] report evacuation distances of 0.8 km for explosives, 2 km for flammable liquids and 3 km for oxidizers as specified by the U.S. DOT. In this study the exposure radius was calculated based on the actual evacuation area for each material being transported. An Emergency Response Guidebook prepared by CANUTEC *Canadian Transportation Emergency Center* [6] operated by the Transport Dangerous Goods Directorate of Transport Canada, specifies the area to be evacuated.

Chapter 5

Model Formulation

5.1 System Definition

As our industrial society's appetite grows for products and manufacturing processes that require the shipment of hazardous materials, so grows the amounts of hazardous materials passing through communities, the resulting accidents and the need for some means of assessing community risk before accidents happen. A transportation model is developed to access the safety of certain cities, through which hazardous materials are being transported. A model is defined as a representation of a system for the purpose of studying the system. Since not all details of the system are considered, the model is not only a substitute for a system; it is also a simplification of the system [34].

A model should be sufficiently detailed to permit valid conclusions to be drawn about the real system. One of the characteristics of this new risk calculating model is that, all the O-D pairs and the number of shipments between these O-D pairs are actual data obtained from Statistics Canada. Also, in this research, we present an assessment of the hazmat transport risk in a multi-commodity and multi origin-destination setting. In order to understand the dynamics of this model, a number of terms have to be defined:

An *entity* is a physical object of interest in the transportation system (e.g., vehicle, bridge, intersection). The transportation system consists of the transportation network, the transportation modes and the different materials. The transportation network consists of nodes, links, locations and segments of interest. *Nodes* are defined as geographical locations where a shipment has at least two alternatives for continuing its trip, such as road intersections, harbors and rail stations. Consequently, nodes are also called decision points. *Links* are direct connections between two nodes. Examples of links are air sectors, roads, rivers and rail tracks. The modes used to perform the shipments can be divided into three classes: land (truck, car, train), water (inland, offshore, open water) and air. The different materials were discussed in Chapter 3.

An *attribute* is a property or a characteristic of an *entity*. For example, some of the attributes of the entity "vehicle" are speed, probability of brake failure and fuel consumption. The *variables* of the risk assessment model refer to the attributes and are also called *attribute-variables*. *General variables* are (usually constant for the transit phase) the available technology to support monitoring and guidance of vehicles and drivers (or captains and pilots), regulations, culture, and ownership. Specific variables refer to the hazardous materials, location and destination, the transportation modes, routing and scheduling. Detailed variables refer to the environment (population, aquifer, road traffic, etc.), the state of material, the condition of driver (or captain and pilot) and the state of the vehicle (e.g., speed, brake condition, engine condition).

The variables of control refer to the two attributes that are important for this decision model: risk and cost. Consequently, the control model is also called *risk model*. The other variables used to describe risk and cost are called *the parameters of control* (risk and cost parameters).

Figure 5.1 shows the *Risk* and *Cost Entities*. *Risk-entities* are physical objects with special interest for risk aspects, *cost-entities* are underlying physical

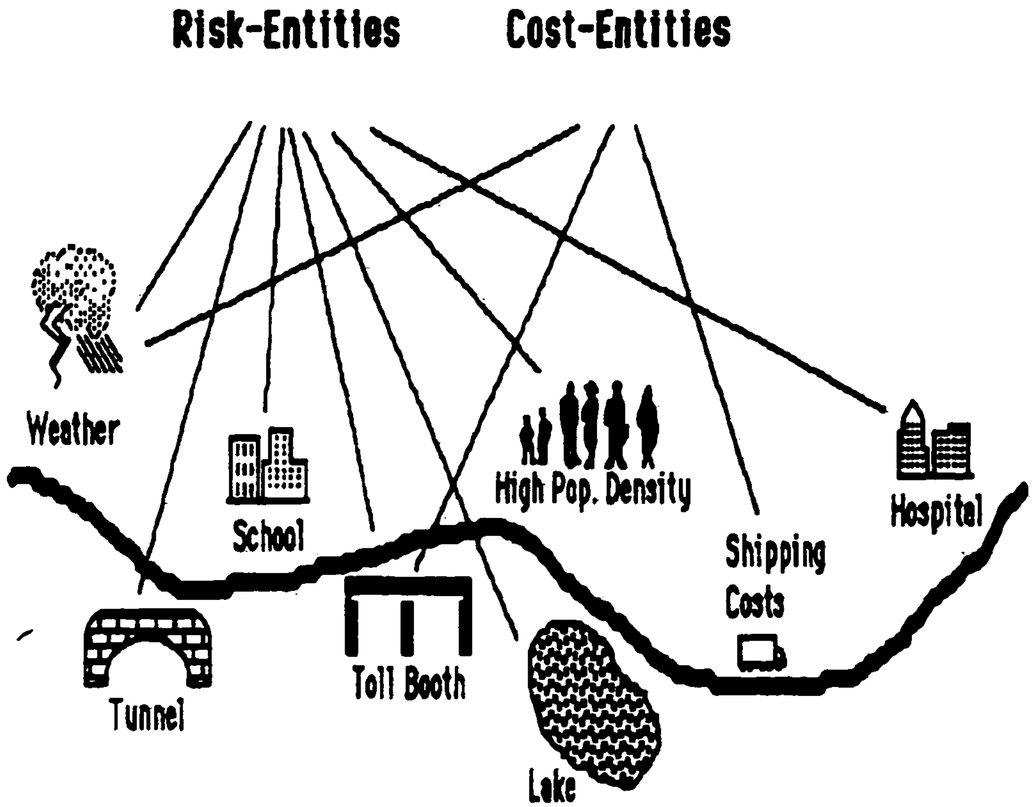

Figure 5.1: Risk and cost entities
[3]

objects with special interest for cost aspects. However, there might be physical objects, which are both risk-entities and cost-entities (road type; e.g., highway). The *state* of the system is defined as the set of variables (state variables) necessary to describe the system at any time, relative to the objective of the study.

5.2 Risk Assessment as a Basis for Evaluating Overall Safety

Risk assessment involves determining the frequencies and consequences of undesirable events, then evaluating the associated risk in quantitative terms [40]. When adequate information is available, this number can be computed directly from historical data; otherwise more theoretical approaches to risk estimation are required. The risk measure of interest can vary considerably, but typically risk in hazardous materials transport is expressed in terms of expected damages, injuries or fatalities (Philipson et al., 1983).

Risk assessment is typically structured as a sequential process, beginning with the level of involvement (e.g., number of shipments, tons carried, distance moved etc.), the frequency and the type of incident occurrence (e.g., tank truck roll over, loose fitting, dropped in handling, etc). The way these components are defined and measured depends on the data availability, the purpose of the risk assessment, and the preferences of the risk analyst (Philipson et al., 1983). As indicated in Chapter 4, in the area of truck transport of hazardous materials, there have been widely varying applications of risk analysis. They have been characterized by generic treatment of hazardous materials or focus on a single substance or class and have included a diverse set of risk measures.

The estimated consequence of an incident involving a shipment of hazardous materials depends on a variety of factors including the amount released, toxicity of the chemical, health effects from the material that is released, population and environmental characteristics adjacent to the incident site and the weather conditions at the time of the incident. The interplay among these factors produces the risk spectrum for transporting hazardous materials.

5.2.1 Routing Based on Risk

The routing problem involves selecting paths for hazardous materials between one or more origin-destination (O-D) pairs. Selection of the path depends upon the risk analyst and the purpose of the risk assessment. The path required for any O-D pair should be "optimal" path for that case. (e.g. "optimal" may mean the best path that reduces one of the following risk, cost, distance between O-D, exposure or a combination of the above for that O-D pair). One such model [35] minimizes the number of people with in "P-neighborhoods" of the links traversed by the route. Another model that [14] focuses on minimizing total risk. A third model [45] focuses on Societal/Traditional Risk. And the fourth model is the traditional minimum distance model which reduces the distance between O-D pairs in order to reduce the cost.

5.3 The Programming Environment

The major capabilities the programming environment should possess are, managing data (routes), performing sufficiently fast algorithmic calculations along with an user friendly environment. For these purposes, several programming environments have been investigated. These include Pro-E, VSE (Visual Simulation Environment), Visual Basic (6.0) and Visual C++(6.0). Visual Basic(6.0) was found to be the most appropriate programming environment for meeting the above requirements. Visual Basic offers a user-friendly programming environment in contrast to other environments, which either require an experienced programmer or are not flexible enough to solve many user-specific tasks. JDK 1.2.2 *Java Development Kit* was used to calculate the area of intersection between a danger circle and a polygon.

The underlying programming methodology is based on Object Oriented Programming (OOP). The links, routes, cities, places, vehicles and accidents (objects) can contain text, graphics, executable programs or any other form of multimedia information and procedures (e.g., video and sound). The object oriented links represent relationships between two links, which can consist of sending a message, linking O-D, activating a successor link, "jump" to another link or any other relation. OOP has advantages over sequential processing. It offers more flexibility and power in the development as well as in the execution phase, so that traditional programming languages have been embedded into OOP concepts, such as 'C' programming language.

5.4 Data

As discussed in chapter 2, the data about transportation of Hazmats within Ontario, Quebec and between the two provinces was obtained from Transportation Division, Statistics Canada. Gasoline, Fuel Oil, Petroleum & Coal tar and Alcohol constitute 56% of all the hazmats transported via the Canadian Highway network. We focused on truck shipments of Gasoline within Ontario for our research. The main reason being that, the highway road network in Ontario is widely spread as compared to the highway road network in Quebec, where the network is not too widespread.

In 1998, there were 135,020 truck shipments of the above four hazmats within Ontario. Out of these 59,909 truck shipments were of Gasoline, which represent 45% of the total four materials. Fuel Oil was next the hazmat material widely transported which accounted for 30% of four material transported then followed by Petroleum & Coal tar and Alcohalic deriavaties respectively. Also these 59,909 truck shipments were made between 140 O-D pairs within Ontario. Since the records do not contain reliable information with regards to the amount of hazmat carried, this focuses on the number of shipments between each pair. A Pareto analysis was made to select a few 0-D pairs, so as to reduce the size of the problem and also at the same time the selected O-D pairs should represent the over all complexicity of the problem. Hence a pareto analysis was performed on the 140 O-D pairs and out of them, 20 O-D pairs were selected which covered 56% of the total trucks and 70% of the total truck-km. The number of trucks between these 20 O-D pairs are shown in Table A.5. Also this road network was found to be widely spread and covered most of the important cities within Ontario.

5.4.1 Database

The province of Ontario is used as the setting for the case study. The province of Ontario has 543 census sub-divisions, as per 1996 population census. Toronto and York are the two most densely populated sub-divisions in Ontario with 5028 and 4884 people per square kilometer, respectively. We focused on the census sub-divisions with a population density larger than 500 people per square kilometer. Thus our model includes 27 zones with a total population of 5.8 million.

These zones include twenty one major cities - Toronto, Mississagua, Brampton, Burlington, Waterloo, Kitchner, Oshawa, London, Oakville, York, North York, East York, Markham, Ajax, Scarabrough, St.Catherines, Peterbrough, Etobicoke, New Market, Aurora and Richmond Hill. Most people live in these cities and in the immediately surrounding towns. Also many local industries in these zones produce hazmats which are shiped through these zones.

We used the highway network of Ontario that is provided with ESRI's *Environmental Systems Research Institute* ArcView 3.1 GIS software. The transportation network is coded in terms of links, nodes and the attributes for the individual links. Nodes represent intersection points of road sections, while links represent section of the road between the nodes. Link attributes are defined in terms of its distance, population exposure units, environmental component exposure units, population risk units and environmental risk units. Length of each link is obtained from the highway map of Ontario. The distance for each link of the study region is measured and recorded in a database. Link attributes that are taken into consideration are link distance (km), population density of each city (persons/sq km), population risk units (threshold km) and also the co-ordinates of each link, node and cities were obtained from the map.

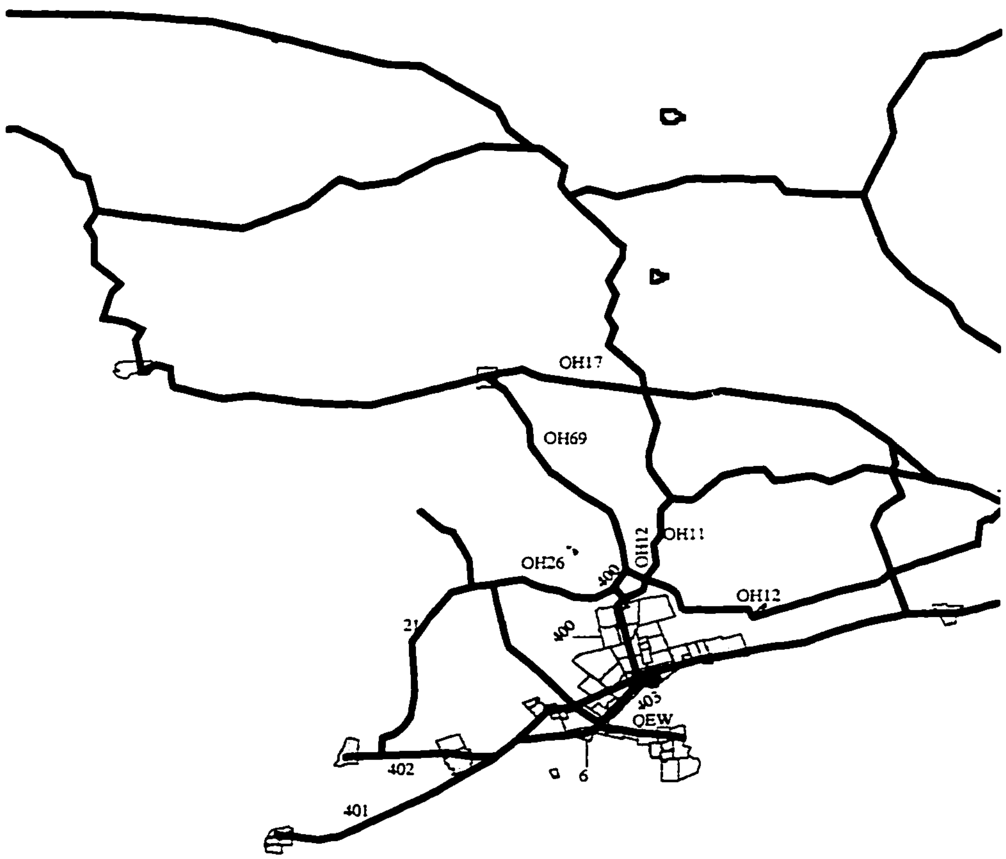

Figure 5.2: Map of the Ontario highway road network

Figure 5.2 shows the entire highway road network within Ontario. Figure 5.3 is the network used for the case study. The figure shows links, nodes and the

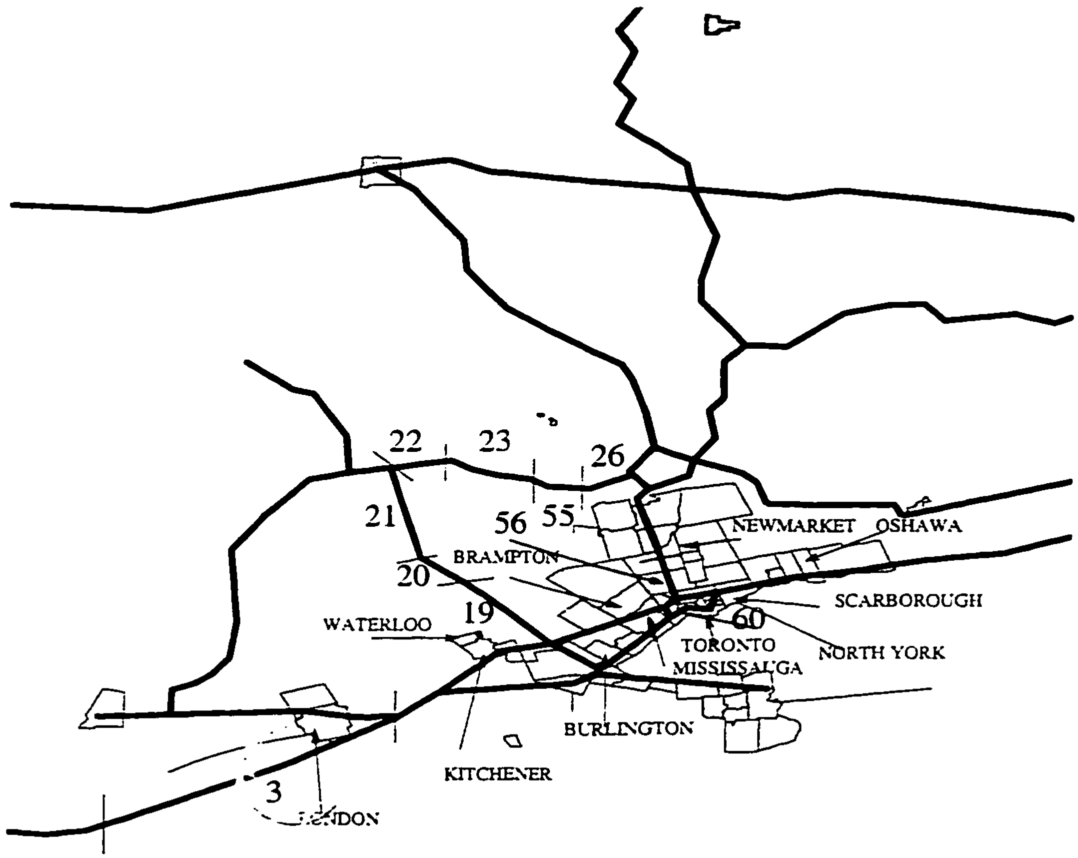

Figure 5.3: Case study network

polygons through which the hazmats are being transported. The highway road network was obtained using GIS software from the data provided by Statistics Canada. The road network contains 105 links and 103 nodes.

5.5 Population Exposure (Persons)

Representation of the spatial distribution of population, within the geographical region of concern, is another crucial issue in hazmat transport risk assessment. A very common model in the literature is the point representation of population centers. That is, each population center is modeled as a point on the plane, and all of the people living in that center are considered to be affected from an incident if the point representing the center lies within the impact area of an incident. Traditionally, the impact area of an incident is assumed to be a circle centered at the incident location and it is called the "Danger Circle". The radius of a danger circle depends on the type of hazmat being shipped. Recently, Erkut and Verter (1995) [44] proposed an extended model, in which population centers are represented as polygons rather than points.

Figure 5.4 shows the extended model, which depicts a road segment 'S' passing through population center 'i'. A hazardous materials vehicle travelling from left to right on the road segment enters the population center at point a and leaves at point d. The impact area 'i' around the segment (a,d) is determined by the threshold distance λ_m, for the hazardous material M being carried. According to the threshold distance approach, an individual in the impact area will be affected by a material M incident, if it occurs within a distance of λ_m. Therefore, a person at point e will be in the hazard area of a material M incident when the vehicle is traversing segment (b,c). Note that the length of (b,c) depends on the location of point e, and it becomes longer as point e gets closer to the road segment. The societal risk

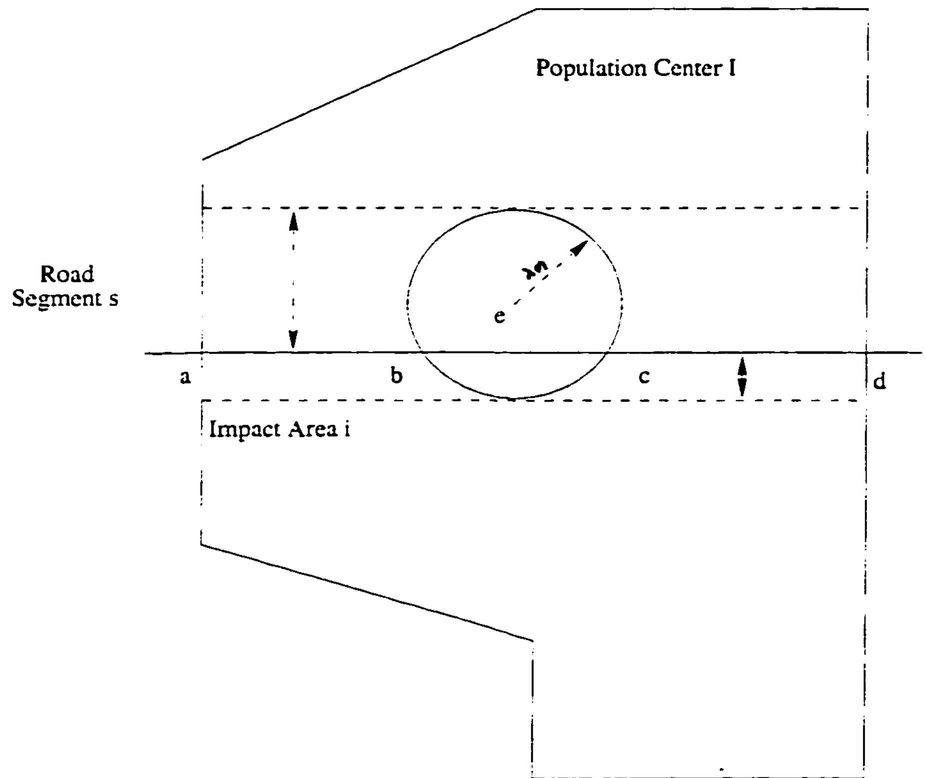

Figure 5.4: Risk assessment with the extended model

$$R_{ism} = P_{sm}(I)(POP_{i'})\lambda_m(\pi/2) \quad (5.5.1)$$

Clearly, the polygon representation of population centers improves the accuracy of a risk assessment framework, and hence we use this approach in our analysis.

The population exposure unit is the number of people exposed in the evacuation area (danger circle), which is a circular area of radius 0.8 kms around the accident site for Gasoline. The affected area is the region encompassed by this circular area with the boundaries of the adjoining cities, which are assumed to be rectangular in shape. This affected area when multiplied with the population density of that particular city gives us the number of individuals exposed. The population densities for the population centers is obtained from a demographic map obtained from Statistics Canada. The census sub division map for the region was used to obtain the demographic map. This map divides the region into smaller regions and municipalities. The area and population of each region or municipality are obtained from the demographic map obtained from Statistics Canada. The population density of each city is obtained by dividing population of that city with its area. The population density for all the other cities is obtained by the same procedure.

5.6 Assumptions

The assumptions made, including those imposed by data limitations, are as follows:

5.6.1 Assumption 1: p_s is constant on link S

Note that any transport network can be redefined so as to satisfy Assumption 1. It is possible to decompose a link that violates this assumption into sub-links, each with constant incident probability. Thus, the probability of having an incident on unit segment k of link S is $(1 - p_s)(p_s)$. Let $p_s^{'}$ denote the probability of having an incident on link S, and l_s denote the length of link S. Observe that,

$$p'_s = p_s + (1-p_s)p_s + (1-p_s)^2 p_s + ... + (1-p_s)(l_s-1)p_s = \sum_{i=0}^{l_s-1}(1-p_s)^i p_s \quad (5.6.1)$$

Given that the incident probabilities are in the order of 10^{-8}, the following assumption is quite common in the hazmat literature:

5.6.2 Assumption 2:

Without loss of generality, let P = 1,2,..., r . The incident probability of a single shipment on path P is:

$$p'_1 + \sum_{s=2}^{r}\prod_{k=1}^{s-1}(1-p'_k)p'_s \quad (5.6.2)$$

Based on Assumptions 1 and 2, the incident probability of path P simplifies to:

$$\sum_{s=1}^{r}(p_s)' = \sum_{s=1}^{r}(p_s)(l_s) \quad (5.6.3)$$

5.6.3 Assumption 3: d_s is constant on link s.

Let d_s denote the population density around a unit road segment on link s . Again, by redefining links, any transport network can be transformed so as to satisfy Assumption 3. Thus, let $C_{s,m}$ denote the number of people living within the danger circle of hazmat type m around link s, and λ_m denote the impact radius of hazmat type m .

$$C_{s,m} = \Pi\lambda_m^2 d_s \quad (5.6.4)$$

The Societal or Traditional Risk of a single shipment on path P is the expected number of people that will be affected as a result of an incident during transportation. Based on the assumptions mentioned above the societal risk of path P simplifies to:

$$\sum_{s=1}^{r} p_s' C_{s,m} = (\sum_{s=1}^{r} l_s p_s d_s) \Pi \lambda_m^2 \qquad (5.6.5)$$

The Population Exposure of a single shipment on path P is the total number of people that will be exposed to the potentially hazardous vehicle. It is possible to consider the hazmat shipment over a link as the movement of the danger circle along that link. This movement carves out a band, on both sides of the link that is the region of possible impacts. We refer to that area as the exposure zone, and denote the exposure zone of hazmat type m around link s as $EZ_{s,m}$. Let $C_{s,m}$ in represent the number of people living in $EZ_{s,n}$.

When link s is a straight line

$$C_{s,m} = d_s(21_s \lambda_m + \Pi \lambda_m^2) \qquad (5.6.6)$$

Clearly, the population exposure of path P is:

$$\sum_{s=1}^{r} C_{s,m} \qquad (5.6.7)$$

5.6.4 General Assumptions: Based on Data limitations

Many of the Origin and Destination points are not on the highway network. We assumed that the trucks would be required to use the shortest route when they are off the highway network. This is a plausible assumption within many municipalities, especially in large population centers. Thus, we projected each origin and destination point onto the closest highway link, and used the resulting points as the origins and destinations in our model.

Chapter 6

Methodology

6.1 Introduction

The methodology used in this study to assess risk on certain cities due to transportation of hazmat within the vicinity of the cities can be considered as a multi Origin - Destination transportation model. This is again broken down into many single Origin - Destination, single commodity flow transportation model. The methodology also uses historical data of hazmat truck accidents.

The methodology to determine minimum exposure routes and risk optimization in the transportation of HM is made up of four stages, and each stage deals with a different aspect of the risk analysis process.

6.2 Methodology

6.2.1 Stage I : Database

In the first stage, after selecting the region for the case study, the highway road network for the region is obtained. From the historical data, the Origin - Destination pairs are selected and analyzed based on the commodity transported. Our road network was based on the analysis made on Gasoline. Thus if the commodity is changed then, some of the Origin - Destination pairs change and hence we will have a different kind of road network. A database is developed for the highway network. This is done through a series of overlays of maps. The highway map is coded into nodes and links. These are points of references. The database used is Microsoft Access which contains the following tables:

Input This table contains the input information entered by the user to run the simulation. The table contains information about the Origin - Destination of the truck shipment, route on which the material is to be shipped, the number of vehicles, shipment time, starting time of the shipment. This table is used to modify the input information, if the user had made any errors while entering it.

Characteristics This table contains the data of characteristics of the materials that is being transported. The table also provides the area of the dangerous circle for each material.

Location This table contains the information about the location (co-ordinates) of the Origins and Destinations with respect to the map.

Links This table contains information about the links in the road network. It also contains the co-ordiantes of the links with respect to the map, length of each link on the map and the actual distance of each link on the road network.

Route The route table contains information about the routes which are used by the trucks to transport Gasoline between the assigned O-D pairs. There are four different types of routes between each Origin - Destination pair as stated before. Hence depending upon the route type, the route between that Origin - Destination changes. The table also gives us the origin and destination of the route and what kind of route it is (e.g. shortest path, minimum exposure, minimum population...). Actual length of the route is also stored in the table.

Route link This table contains information regarding the total number of links in each route. These links which are in sequential order in the table gives the direction of the movement of the vehicle.

Vehicles This table contains the information of vehicles. Once the user inputs the information in the program, the program generates the required number of vehicles in the vehicle table with an unique ID for each vehicle. It holds all the information about the vehicle i.e., the starting time of the vehicle, the status of the vehicle (reached destination, accident, not started), the route on which it is traveling, the length of the route. Also, if the vehicle meets with an accident, it will tell us on which link the accident has occurred and at what distance from the starting point the accident has occurred.

Accident info This table contains the information of all the vehicles which have met with an accident. This table contains the information regarding, the vehicle ID, the co-ordinates of the point of accident with respect to the map, on which route and link the accident has occurred and if the accident has any incident.

Cities This table contains information about all the cities which come under the area of study. The table has the information about the density of the city, population of the city, area of the city, co-ordiantes of the city with respect to the map. The table also gives you the affected area if any and the number of people to be evacuated due to the hazmat accident.

6.2.2 Stage II : Routes

The objective of the second stage, is to determine the routes between the Origin-Destination pairs. Four different routes between each Origin - Destination were obtained. The minimum paths for shortest distance, minimum population exposure units, minimum probability and minimum risk exposure units are determined.

The basic hypothesis is that a minimum path can be found between th O-D pair if the link attribute on a highway network is defined, and the total attribute on the path is minimized. We used the Dijkstra implementation provided in the network analyst extension of ArcView 3.1.

A minimum path between the given O-D pair using a specific link attribute, for example, population exposure units, gives a route that has the minimum number of people exposed on it. The model developed by Batta and Chiu [35] is used to determine the minimum population exposure route.

Similarly for the minimum path between the given O-D for risk exposure and minimum probability incident units, we used methods suggested by Erkut and Verter [45] and Saccomanno and Chan [14] respectively.

6.2.3 Stage III : Simulation of the System

The flow chart of the program is shown in Figure 6.1. Once the user enters the information about the truck shipments, this information is saved in the database for each vehicle. Here each vehicle will be assigned a unique number on which information is stored. This includes start time, origin, destination, cargo, route and distance to travel. A vehicle can be in one of two situations : either on the road or idle. This is determined from the start time, which each truck is assigned. Start time indicates when the truck should start from their respective origins.

Now the program enters in to second level, here it moves the vehicle on the assigned route for that vehicle. For that, the program checks for the system time and

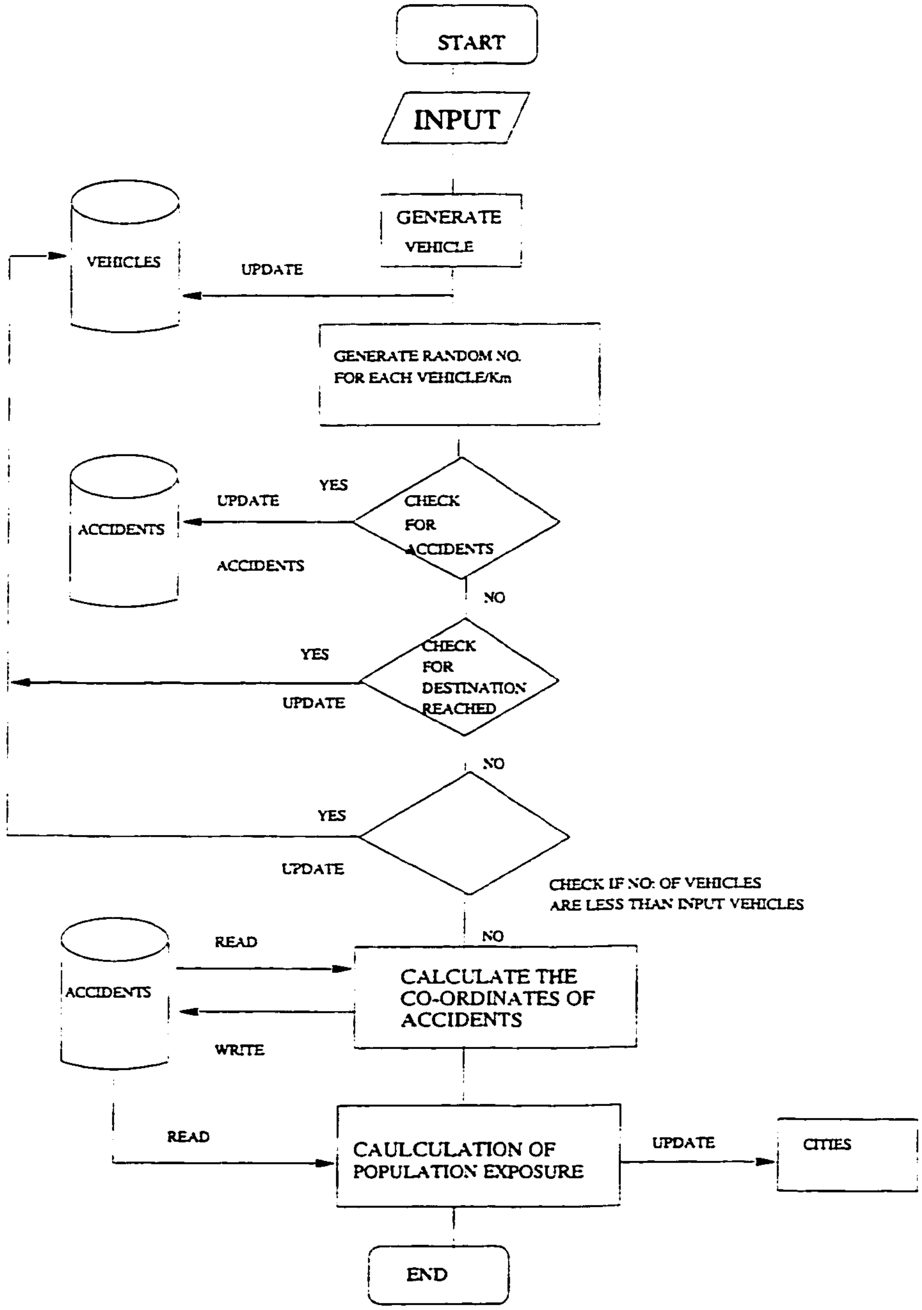

Figure 6.1: Flow chart for methodology

the start time of the truck. If the start time of the truck equals to system time then the vehicle is started automatically. This condition is checked for all the vehicles in the system and it will start all the vehicles which satisfy the above condition.

But before starting the vehicle from the origin, the probability of accident for each vehicle is checked for one km length of segment of that link. If there are no accidents then the vehicles will be moved to a distance of one km. Here the links are divided into small parts called "segments" each of length one km. Once the probability of accident is checked for each segment and for all the vehicles that are moving, then if there are no accident due to the probability, the vehicle is moved ahead to the next segment.

This process is continued until the vehicle/vehicles reach the destination or the truck is met with an accident. At the same time the program checks for the start time of the remaining vehicles that have not started. If the start time of any one of the remaining unstarted vehicles equals the system time then the program starts those vehicles and starts to move them simultaneously along with the other vehicles following the above procedure. Then the vehicles will be moved further on the respective routes/links as explained above.

Here the important aspect to be noted is that, the program checks the probability of accident for each vehicle/segment separately and moves the vehicle accordingly. Also at the same time it starts the vehicles that have to be started once their start time equals the system time. If the truck comes across an accident, then all the information regarding the truck is moved into the accident table. Here the co-ordinates of accident point, the link on which the accident has occurred and the distance of the accident point from the origin is calculated.

Once computations are made, further probability of incident is checked for the accident. Here the probability of incident is checked, if there is an incident then, based on the point of accident the program will calculate the number of people to be evacuated from the accident site. This process continues untill all the trucks reach the destination or they meet with an accident.

Before exiting from the simulation, the program will update the cities table. From the cities table we can find out the affected area due to an incident of hazmat vehicle. The table shows the amount of area affected under each city and the number of people to be evacuated over the period of one year.

6.2.4 Stage IV : Analysis

The risk analysis process is carried out in the fourth stage. The total risk due to the movement of hazmat trucks, through the region in terms of amount of area effected and the total number of people to be evacuated at the end of the year is calculated. The risk on each link of the network can be calculated, to determine the worst link (i.e., a link with maximum number of accidents) in that O-D pair.

A number of analysis are performed using alternative criteria and criteria weights. These range from a route designation based on minimizing risk to population, to one based on minimizing cost. Several additional applications performed in which both criteria are considered simultaneously, applying corresponding weights to each criterion, reflecting various levels of relative importance. The minimum normalized risk units are then plotted against the criteria weights and the combination of relative weights that optimizes risk is obtained from the curve. The best route where the risk is optimized is then designated using this combination of relative weights.

Chapter 7

Analysis of Results

7.1 Introduction

The results on the amount of risk on the cities through which hazmats are being transported are reported in this chapter. The province of Ontario is chosen as the study region and 22 pairs of Origin-Destination are used for this analysis. These cities include Toronto, Mississauga, London, Etobicoke, Markham etc.

7.2 Minimum Exposure Routes

Minimum exposure routes are routes between the O-D pairs on which a specific exposure unit on the route is minimized. Three criteria were used to obtain the minimum paths. The criteria used were:

- Minimize Shipment distance (Min Length).
- Minimize Societal risk (Min Risk).
- Minimize population exposure (Min Exposure).
- Minimize Incident Probability (Min Probability).

Each criterion yielded a different minimum path. The results of which are illustrated in the following sections.

7.2.1 Minimize Shipment Distance (Min Length)

Using the criterion to minimize shipment distance to obtain the minimum path, the distance (km) of the links of the transportation network is used as the link impedance in the route-building algorithm. This resulted in the selection of the routes with the minimum distance between the O-D pairs. This route is designated Min Length. The total distances between the O-D pairs are computed and tabulated in A1, Appendix A.

The Population Exposures or the number of people to be evacuated from each city due to a hazmat accident on the Min Length route for the various O-D pairs are computed and tabulated in Table 7.1. Table 7.2 shows accidents on some of the important links for shortes path route.

7.2.2 Minimize Societal risk (Min Risk)

The risk on the links of the highway network is used as the link impedance in the route-building algorithm i.e., the expected number of people to be evacuated in case of an accident. The routes selected are those with the minimum amount of people exposed on them between the O-D pairs. These routes are designated as Min Risk routes. The distances between the O-D pairs are computed and tabulated in A2, Appendix A.

The Population Exposures or the number of people to be evacuated from each city due to a hazmat accident on the Min Risk route for the various O-D pairs are computed and tabulated in Table 7.3. Table 7.4, lists the number of accidents on each link with more than 50 accidents.

CSName	Population	Density	Area	Area Effected	Pop.Effected
Ajax	64430	805	93467	0	0
Aurora	34857	580	69266	92	534
Brampton	268251	849	372125	26	232
Burlington	136976	652	263718	23	150
East York	107822	5391	29377	54	2911
Etobicoke	328718	2191	188893	234	5128
Kitchener	178420	1189	190784	52	619
London	325646	986	579817	28	276
London	325646	692	404664	0	0
Markham	173383	722	296668	0	0
Mississauga	544382	1555	436494	110	1710
Newmarket	57125	1428	53201	52	743
North York	589653	2948	243932	17	501
Oakville	128405	755	210926	4	30
Oshawa	134364	707	230808	48	339
Peterborough	69535	1158	76478	40	464
Richmondhill	101725	924	141113	165	1526
Scarborough	558960	2661	265563	110	2928
St.Catharines	130926	818	194177	110	900
Toronto	653734	5028	1594647	78	3922
Waterloo	77949	1113	89505	60	668
York	146534	4884	32271	10	488

Table 7.1: Total population exposed in each city due to hazmat transportation using shortest path route criterion

7.2.3 Minimize Population Exposure (Min Exposure)

The Population Exposure (persons) on the links of the highway network is used as the link impedance in the route-building algorithm. The routes selected are those with the minimum amount of people exposed on them between the O-D pairs. These routes are designated as Min Exposure. The total distances between the O-D pairs are computed and tabulated in A3, Appendix A.

The Population Exposures or the number of people to be evacuated from each city due to a hazmat accident on the Min Exposure route for the various O-D pairs are computed and tabulated in Table 7.5. Table 7.6, lists the number of

Acct.Link	Count Of Acct.type
3	96
29	59
46	31
45	25
48	53
56	119
60	96
82	66

Table 7.2: Number of accidents on each link using the shortest path route criterion

accidents on each link with more than 50 accidents.

7.2.4 Minimize Incident Probability (Probability)

The probability of an incident on the links of the highway network is used as the link impedance in the route-building algorithm. The routes selected are those with the minimum amount of people exposed on them between the O-D pairs. These routes are designated as Min Probability routes. The total distances between the O-D pairs are computed and tabulated in A4, Appendix A.

The Population Exposures or the number of people to be evacuated from each city due to a hazmat accident on the Min Risk route for the various O-D pairs are computed and tabulated in Table 7.7. Table 7.8, lists the number of accidents on each link with more than 50 accidents.

7.3 Detailed Analysis

From the previous data, three incidents were reported in the study region. These incidents occurred at London, Gogama and Orillia. Assuming that the carriers use shortest path between the O-D pairs, the simulations for shortest path indicatehigh accident rates on link numbers 56, 60 and 3. Apparently link 3 passes close to London, where the actual incident has occurred. From the shortest path route

CSName	Population	Density	Area	Area Effected	Pop.Effected
Ajax	64430	805	93467	0	0
Aurora	34857	580	69266	178	1034
Brampton	268251	849	372125	208	1859
Burlington	136976	652	263718	101	658
East York	107822	5391	29377	89	4798
Etobicoke	328718	2191	188893	428	9379
Kitchener	178420	1189	190784	165	1922
London	325646	986	579817	81	799
London	325646	692	404664	18	124
Markham	173383	722	296668	0	0
Mississauga	544382	1555	436494	192	2986
Newmarket	57125	1428	53201	145	2070
North York	589653	2948	243932	218	6427
Oakville	128405	755	210926	4	30
Oshawa	134364	707	230808	84	594
Peterborough	69535	1158	76478	237	2746
Richmondhill	101725	924	141113	205	1895
Scarborough	558960	2661	265563	308	8198
St.Catharines	130926	818	194177	192	1571
Toronto	653734	5028	1594647	76	3821
Waterloo	77949	1113	89505	108	120
York	146534	4884	32271	47	2295

Table 7.3: Total population exposed in each city due to hazmat transportation using minimum population route criterion

criterion simulations, the accident rate is relatively high on links 46, 50 and 47. These three links intersect in Gogama. This indicates the validity of our model.

From our analysis, maximum number of people were evacuated from Etobicoke, irrespective of the routing criteria used for shipping hazardous materials. The number of people exposed to risk are 10847 under MinExpo, which reduced to 9379 under MinPoP, 6201 under MinRisk and 512 under MinLength. Our analysis showed that maximum number of incidents were occurring on links 56, 57, and 60 which were passing through Etibicoke as shown in the above tables.

One of the interesting results of our analysis was, Toronto was showing maximum values in the minimal risk routing model. In a way, this result sheds light

Acct.Link	Count Of Acct.type
3	86
55	105
56	183
60	111
67	59
82	71

Table 7.4: Number of accidents on each link using the minimum population route criterion

on the fact that since it is a densely populated area, the number of people exposed to risk will be obviously high as shown in Table 7.7.

A comparison of number of accidents, incidents and number of people evacuated are shown in Table 7.9. From the table, we can observe that shortest path has minimum number of accidents and the number of people evacuated are low, where as Min Population route has maximum number of accidents and the number of people evacuated are high.

As discussed earlier, we have assumed that the trucks use shortest path to transport hazmats between the O-D pairs. The number of people to be evacuated due to hazmats transport on shortest path route is 1094. From Transport Canada data, we know that 1090 people were evacuated in the province of Ontario due to gasoline shipments. This indicates the validity of the model.

An important inference that can be drawn from Table 7.9 is that the expected number of evacuations will increase by 126%, 51% and 194% for Min Population, Min Risk and Min Exposure, respectively.

The resultant F-N curves for road transport of Gasoline are downward sloping. As the number of fatalities N increases, the cumulative frequency of incidents per year reduces rapidly. As shown from Figure 7.1, we can see how the risk increases if the trucks were to take Min Exposure route instead of Min Length route. The thickness of the line represents risk.

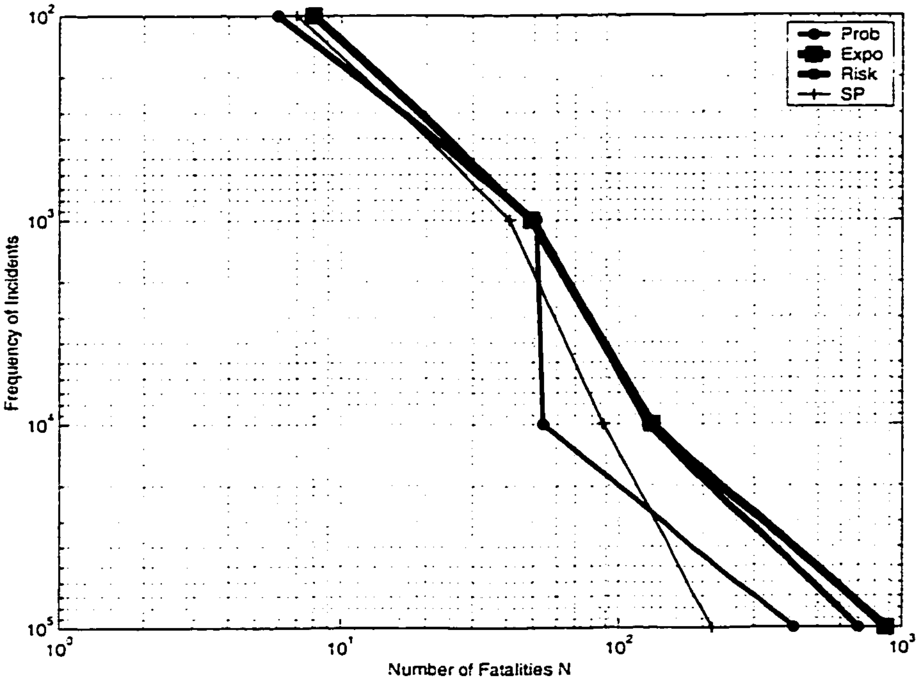

Figure 7.1: Fn Diagram

CSName	Population	Density	Area	Area Effected	Pop.Effected
Ajax	64430	805	93467	0	0
Aurora	34857	580	69266	205	1190
Brampton	268251	849	372125	279	2494
Burlington	136976	652	263718	109	710
East York	107822	5391	29377	170	9164
Etobicoke	328718	2191	188893	495	10847
Kitchener	178420	1189	190784	206	2450
London	325646	986	579817	128	1263
London	325646	692	404664	12	83
Markham	173383	722	296668	0	0
Mississauga	544382	1555	436494	211	3281
Newmarket	57125	1428	53201	194	2770
North York	589653	2948	243932	221	6515
Oakville	128405	755	210926	0	0
Oshawa	134364	707	230808	153	1081
Peterborough	69535	1158	76478	313	3627
Richmondhill	101725	924	141113	220	2034
Scarborough	558960	2661	265563	381	10141
St.Catharines	130926	818	194177	211	1726
Toronto	653734	5028	1594647	116	5833
Waterloo	77949	1113	89505	119	1325
York	146534	4884	32271	90	4396

Table 7.5: Total population exposed in each city due to hazmat transportation using minimum exposure route criterion

Acct.Link	Count Of Acct.type
3	76
17	55
19	292
20	161
21	286
22	120
23	114
25	79
26	77
44	55
48	70
61	200
82	70
94	52

Table 7.6: Number of accidents on each link using the minimum exposure route criterion

CSName	Population	Density	Area	Area Effected	Pop.Effected
Ajax	64430	805	93467	0	0
Aurora	34857	580	69266	110	639
Brampton	268251	849	372125	26	232
Burlington	136976	652	263718	30	196
East York	107822	5391	29377	110	5930
Etobicoke	328718	2191	188893	283	6202
Kitchener	178420	1189	190784	84	999
London	325646	986	579817	69	681
London	325646	692	404664	30	208
Markham	173383	722	296668	0	0
Mississauga	544382	1555	436494	116	1804
Newmarket	57125	1428	53201	78	1114
North York	589653	2948	243932	47	1386
Oakville	128405	755	210926	0	0
Oshawa	134364	707	230808	101	714
Peterborough	69535	1158	76478	35	406
Richmondhill	101725	924	141113	222	2053
Scarborough	558960	2661	265563	134	3567
St.Catharines	130926	818	194177	116	949
Toronto	653734	5028	1594647	144	7241
Waterloo	77949	1113	89505	63	702
York	146534	4884	32271	26	1270

Table 7.7: Total population exposed in each city due to hazmat transportation using minimum probability route criterion

Acct.Link	Count Of Acct.type
3	89
17	81
19	210
20	149
21	282
22	157
23	205
24	55
25	79
26	101
40	73
48	50
61	163
82	79
85	78

Table 7.8: Number of accidents on each link using the minimum probability route criterion

city	Accidents	Incidents	Evacuation
Shortest path	14	3	1094
Population	33	7	2475
Probability	16	4	1650
Exposure	28	6	3225

Table 7.9: Total risk due to gasoline shipments in the province of Ontario

Chapter 8

Conclusions and Future Work

This research has presented an integrated model that decision makers from both industry and government can use to analyze the routing and risk assessment problems for hazardous materials transportation. On the way of our study, we demonstrated an efficient simulation model for minimizing the risk on a region/community through which hazardous materials are transported. The model realistically considered both the network on which the routes and the underlying planes (population centers) where the risk impacts are felt. This chapter summarizes some of the principal observations, conclusions and recommendations for future research in this study area. Some of the important conclusions of this study are:

- This model helps in identifying the sections of highway with high risk, as indicated for London, Gogama, and Oakville. Link numbers 56, 57 and 3 have high accident rates and as these links are passing through highly populated neighborhood, the risk would be high. It is possible to reduce risk by constructing/useing new routes which avoid populated neighborhoods.
- Past research indicated the incident probability to be 0.05 for a highway road network for gasoline shipments, which is a contradiction in our case. The incident probability was found to be 0.21.

- The application of different routing criteria results in the selection of different preferred routes. If minimization of risk on a region/community is the criterion, then a safer route other than shortest route by distance is to be selected. The risk on a region/community will be minimimal in case of an accident on a route designated based on the minimizing exposure units. But the cost of transporting the hazmat (gasoline) will increase as the distance between O-D pairs increases. Hence as a trade off between cost and risk, the best alternative would be to ship on minimum incident probability route.

- The F-N (Frequency of incidents vs number of fatalities) curves obtained from an application of a risk analysis model to the road and rail transport of Gasoline have produced results for actual transportation corridors that are in general agreement with risks reported elsewhere in the literature.

- Regardless of which route is to be taken by hazmat trucks, the computerized model serves a very important purpose in reducing the effects of accidental releases and their impact on populations by providing estimates of hazard areas due to hazmat accidents.

Users of the model

The simulation model developed uses real world data for:

- Geographical information (i.e population centers)
- Demographic information (i.e Number of people prone to hazmat risk)
- Highway road network information
- Accident rate information
- O-D pairs and number of shipments between them

Hence the model developed can accurately predict risk associated with transportation of hazardous materials. Consequently, the model will serve as an invaluable tool to many users including government agencies, general public and industry from various points of view.

For government agencies, the model provides:

- A systematic uniform basis for the identification and evaluation of risks, both the potential chances and the consequences of hazardous materials transportation incidents

- Risk comparison of a commodity shipped in different modal or inter-modal systems

- Risk comparison for different commodities in the same modal system

Evaluation of different regulatory alternatives to show which would result in economic inefficiencies, dislocations, and waste hazardous materials establishments. These organizations can use the model formulation:

- To analyze and identify potential hazards and their consequences

- To promote and reduce risks in advance of design or operational decisions

- To optimize operations and minimize costs

- To improve the safety of existing systems

General Public (Communities) can assess their own:

- Community preparedness or vulnerability

- Emergency response capabilities

- Community levels of safety

Benefits of model

The purpose of this model is to get a clear understanding of hazardous materials transportation and achieve the following goals:

- Describe a community's hazardous materials transportation problem
- Develop support and justification for community budget requests
- Evaluate community enforcement program
- Evaluate or provide adequate training/prevention programs
- Provide proper allocation of resources

8.1 Recommendations for Future Research

Long range planning is essential in the transportation department and industry. The transportation of hazardous materials on the highway system is on the increase and this trend will continue in the near future. Considering these facts, there is a need for further research in the following areas:

- This problem can be further extended to a multi Origin - Destination, multi commodity setting within Ontairo, Quebec and whole of Canada by using a larger database.
- The routing and scheduling methodologies can be enhanced to incorporate a specified departure or arrival time. The algorithms could then track the shipment according to time of day and apply appropriate congestion assumptions to the travel times and use business populations in conjunction with residential populations. These improvements would better support the current business trend toward just-in-time delivery.

- Further, this study can be enhanced by establishing the truck volume and truck accident rates for different types of roadways in Canada.
- Based on the model established, extensive sensitivity analyses can be conducted in an attempt to predict likely future scenarios for increased shipments and new additions to highway infrastructure.

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Appendix A

Appendix

	Toronto M M	H.mand- N.folk	Brant County	Lam.county	Mid.County
Northunberland	202				
Peterborough	306				
Victoria C	228				
Durham R M	209				
York R M	55				
Halton R M	22				
Muskoka D M	214				
Nipssing D	411				
Parry Sound D	255				
Sudbury R M	413				
Timiskaming	599				
Cochrane	992				
Nigara		110			
Peel R M			134		
Wellington c			146		
Halton r m			113		
nigara r m			129		
waterloo r m			79		
essex c				371	296

Table A.1: Total distance on Shortest Path route

	Toronto M M	H.mand- N.folk	Brant County	Lam.county	Mid.County
Northunberland	1274				
Peterborough	1204				
Victoria C	515				
Durham R M	475				
York R M	439				
Halton R M	41				
Muskoka D M	519				
Nipssing D	710				
Parry Sound D	553				
Sudbury R M	814				
Timiskaming	989				
Cochrane	1643				
Nigara		144			
Peel R M			198		
Wellington c			201		
Halton r m			163		
nigara r m			144		
waterloo r m			102		
essex c				789	813

Table A.2: Total distance on Minimum risk route

	Toronto M M	H.mand- N.folk	Brant County	Lam.county	Mid.County
Northunberland	1050				
Peterborough	1012				
Victoria C	494				
Durham R M	474				
York R M	439				
Halton R M	41				
Muskoka D M	502				
Nipssing D	693				
Parry Sound D	506				
Sudbury R M	798				
Timiskaming	877				
Cochrane	1263				.
Nigara		144			
Peel R M			197		
Wellington c			196		
Halton r m			162		
nigara r m			144		
waterloo r m			102		
essex c				772	813

Table A.3: Total distance on Minimum Exposure route

	Toronto M M	H.mand- N.folk	Brant County	Lam.county	Mid.County
Northunberland	217				
Peterborough	324				
Victoria C	238				
Durham R M	217				
York R M	73				
Halton R M	41				
Muskoka D M	246				
Nipssing D	437				
Parry Sound D	277				
Sudbury R M	432				
Timiskaming	620				
Cochrane	1007				
Nigara		144			
Peel R M			197		
Wellington c			196		
Halton r m			162		
nigara r m			144		
waterloo r m			102		
essex c				392	319

Table A.4: Total distance on Minimum Probability route

	Toronto M M	H.mand- N.folk	Brant County	Lam.county	Mid.County
Northunberland	571				
Peterborough	1721				
Victoria C	732				
Durham R M	3469				
York R M	3788				
Halton R M	139				
Muskoka D M	2605				
Nipssing D	1451				
Parry Sound D	1359				
Sudbury R M	1945				
Timiskaming	749				
Cochrane	823				
Nigara		1396			
Peel R M			1434		
Wellington c			845		
Halton r m			2384		
nigara r m			657		
waterloo r m			1105		
essex c				1606	638

Table A.5: Number of Trucks between each O-D pair

Road Type	Urban	Rural
Multi-lane divided	1.11	0.43
Paved Divided	1.89	0.71
Paved Undivided	2.05	0.77

Table A.6: Truck accident rates and release probability for use in hazmat routing and analysis