Determination of Minimum Risk Truck Routes for the Transportation of Hazardous Materials

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ABSTRACT

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Lucy A. Eno

The transportation of hazardous materials is a growing national problem. The percentage of highway accidents that involve hazardous materials and, the amount of damage to population and the environment per accident is increasing. It is therefore necessary to determine routes for their transportation and also minimize the risks involved, in case of an accident.

The methodology described in this thesis involves two major stages. In the first stage, alternative criteria to minimize population exposure units and environmental component exposure units are used to determine routes between origin and destination pairs. An analysis to compare these routes with the shortest distance route is carried out. In the second stage, routes between origin - destination pairs are determined based on population risk units and environmental risk units minimization. Hazardous materials namely, Liquefied Petroleum Gas, Sulphuric Acid and Chlorine gas from three different classes are used. The concepts of normalization, criteria weighting, 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.

A number of computer programs are developed for the determination of minimum exposure and minimum risk routes and for dispersion models. These programs are grouped into two files, namely, [MINROUTE] for minimum exposure and minimum risk routes and, [DISMODELS] for dispersion models.

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LIST OF SYMBOLS

SYMBOL		DESCRIPTION
HM	=	Hazardous Materials
O-D	=	Origin - Destination
GIS	=	Geographical Information System
EPA	=	Environmental Protection Agency
RCRA	=	Resource Conservation and Recovery Act
TDGA	=	Transportation of Dangerous Goods Act
PHR	=	Potential Hazard Rating
R	=	Composite Risk Rate of HM Transport on Route
H	=	Number of incidents that have occured on Route
AR	=	Accident Rate for Route
PR	=	Population - at - risk from any release along route
FR	=	Fatality Rate
$HA_{1\%}$, $HA_{50\%}$	=	Hazard area for 1 and 50 percent lethality
$KR_{30\%}$, $KR_{80\%}$	=	Average 30 and 80 percent kill rates respectively
SF	=	Shield factor for people indoors at time of incident
ADT	=	Average Daily Traffic
ADT_c	=	Average daily traffic volume on combined segments
ADT_i	=	Average daily traffic on Route segment i
L_i	=	Length of Route segment i

SYMBOL		DESCRIPTION
Veh-mi	=	Vehicle miles
$TVMT_i$	=	Annual truck travel(veh-mi) on Route segment i
$TADT_i$	=	Average daily truck volume on Route segment i
TAR_j	=	Average truck accident rate for highway class j
A_{ij}	=	Number of accidents per year on Route segment i in Highway class j
VMT_{ij}	=	Annual vehicle-miles of travel on Route segment i in Highway class j
$P(A)_i$	=	Probability of a hazardous accident for Route segment i
AR_i	=	Accident rate per vehicle-mile for all vehicle types on Route segment i
$P(R)_i$	=	Probability of an accident involving a HM release for Route segment i
TAR_i	=	Truck accident rate for Route segment i
$P(R/A)_i$	=	probability of a HM release given an accident involving a HM-carrying truck for Route segment i
AADT	=	Annual Average Daily Traffic
$AADT_i$	=	Annual Average Daily Traffic volume on segment i
PT_i	=	Percentage trucks on road segment i
Veh-km_i	=	Vehicle - km on road segment i
Acc.$prob_i$	=	Accident probability on road segment i

SYMBOL		DESCRIPTION
RAR_i	=	Releasing accident rate for road segment i
PD_i	=	Population density on road segment i
HA_i	=	Hazard area on road segment i
$Fatal_i$	=	Fatalities on segment i
Fatal/den	=	Fatalities per unit density
R_i	=	Risk on road segment i
$Cons_i$	=	Consequences of an accident on road segment i
Route R1	=	Minimum distance route
Route R2	=	Minimum population exposure route
Route R3	=	Minimum environmental components exposure route
Route R4	=	Minimum population risk route
Route R5	=	75% population risk plus 25% environmental risk route
Route R6	=	50% population risk plus 50% environmental risk route
Route R7	=	25% population risk plus 75% environmental risk route
Route R8	=	Minimum environmental risk route
Route Rmin	=	Minimum risk route

CHAPTER 1

INTRODUCTION

1.1 HAZARDOUS MATERIALS AND THEIR TRANSPORTATION

Hazardous materials (HM), are defined by the Secretary of Transportation of the Department of Transportation in the United States as "those materials which because of their quantity, concentration or physical, chemical or infectious characteristics may pose unreasonable risk to health and safety or property when transported in commerce" [9]. Explosives, flammables, oxidizing materials, organic peroxides, corrosives, gases, poisons, radioactive subtances and etiologic (human disease-causing) agents are included in this definition.

The production and transportation of HM is an unavoidable process in any industrial society. A number of industrial activities of vital economic importance are dependent on the uninterrupted flow of these HM through its transportation network. Although HM production is associated with technological growth and economic development, the danger associated with its accidental release is substantial and sometimes catastrophic to humans and the environment. The high risk to population and damage to the environment has drawn considerable attention at local, national and international levels.

The safe transportation of HM from place of origin to place of destination (O-D) has become a major concern to the general public and government policy makers. Pressure has been placed on the transportation agencies to designate safe routes for HM transport that minimize risk. Therefore, there is a need to develop a better understanding of the risk posed by the various HM, and a methodology to designate safe routes for their transportation.

1.2 HM TRAFFIC ACCIDENTS IN CANADA AND QUEBEC PROVINCE

The movement of dangerous goods is increasing approximately 5% per year [19] and, the number of reportable accidents is also on the rise. Between 1988 and 1992, there were 2270 reportable accidents involving HM and 259 of these were in Quebec [18]. More than one-half of these reportable accidents were by road transportation, 1464 out of the 2270 accidents. Therefore, it is essential to regulate the movement of these HM by rerouting and effective strategies to mitigate the consequences in case of an accident.

1.3 PROBLEM DEFINITION

The production and transportation of HM is on the increase and this trend will continue in the near future. Pressure has been placed on the regulatory process to designate routes for dangerous goods transportation that emphasize safety considerations. In designating these routes, the regulatory agencies are confronted with the problem of either designating the same route for the transportation of all HM or whether it would be safer to designate separate routes for each class of HM. Each class of HM differ from another class according to their physical and chemical characteristics, their dispersion upon breach of containment, and their hazards to humans, plants, animals, lakes, rivers and soil.

1.4 OBJECTIVES OF STUDY

The primary objective of this study is to investigate if the same route should be designated for the transportation of all HM, or if it is safer to designate separate routes for each class of HM. The highway system of the South Central Part of Quebec Province is used in this study. Beyond this primary objective, the study is specifically aimed at establishing the following :

1) To determine the minimum paths between an O-D pair through a highway network using specific criteria.

2) To determine the damage to both population and the environment due to a possible accident involving a truck carrying HM.

3) To develop a better understanding of the risks posed by various classes of HM to population and the environment.

4) To determine a methodology to find the safest and best route to carry a given HM between an O-D pair, where risk is minimized.

5) To review the applications of the study and evaluate its importance in transportation planning and policy.

1.5 STRUCTURE OF TEXT

Chapter 2 of this report outlines the literature review related to HM and the risk involved in their transportation, database development, route designation and truck accident rate model. It describes several previous studies considered important for the present study [2,6,9,11].

Chapter 3 deals with the theoretical background. The concepts of system and the environment, minimum path, transport of HM from origin to destination, accident probability and risk are discussed.

In chapter 4, an explanation on how the database is developed is outlined.It explains how data on distance, population exposure, and environmental component exposure for each link of the highway system are collected and recorded.

Chapter 5 describes the methodology used in study. The various stages of the methodology are outlined, and what is accomplished at each stage of methodology is stated.

Chapter 6 outlines the results obtained in this study. These results include minimum exposure routes, dispersion models, and minimum risk routes. A discussion of the results is also presented.

In chapter 7, the computer programs used in this thesis are described. Flow charts, explanations on how the programs work, and sample input data are presented. These programs include minimum path building program and dispersion models programs.

The major conclusions of this study, and suggestions for further research are outlined in chapter 8.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

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 a methodology to determine safe routes for HM transportation.

2.2 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 a Geographical Information System (GIS). Burrough ,1989, [12], 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 the storage, management and integration of large amounts of spatially referenced data.

Abkowitz, et al, 1990 , [1], 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 interaction of the transportation system with the environment. GIS mapping can intergrate information such as geometric design elements, traffic flow conditions, accident occurrences on highway network with, social and demographic factors, environmental, topographic and geological features to produce data on individual highway segments.

2.3 SELECTING CRITERIA FOR DESIGNATING HM HIGHWAY ROUTES

Several alternative criteria have been recommended for consideration in implementing the policy to designate routes for HM transportation. In 1990, Abkowitz et al, [2], studied the impact of using alternative criteria and criteria weighting for route selection. This was examined through the use of a network tool designed explicitly for HM distribution risk management. A study region consisting of the truck highway network in Southern California was used to illustrate several considerations addressed during the implementation process. A number of findings were reported concerning route selection, risk equity, public perception, and emergency preparedness.

A routing analysis was performed first. The routing analysis components consisted of the following features : system selection, criterion selection, origin-destination (O-D) specification, node/link inclusion or exclusion and, highlight identification. Criteria selection allows the user to identify which routing criteria to apply to the analysis. These criteria aims to minimize shipment distance, minimize travel time, minimize release-causing accident likelihood, minimize population exposure, and minimize risk. Multiple criteria may be selected, and weights on each criterion can be adjusted to reflect the importance of each in defining an effective route.

2.4 RISK ASSESSMENT OF TRANSPORTING HM

Risk assessments of HM transport have recently emerged as a critical need and several models and approaches have appeared. Pijawka et al, 1985, [9], developed a model for HM risk management. The state of Arizona was chosen as the area of study. Various risk assessment approaches to shipping HM along major routes were presented and applied so that transportation routes could be comparatively evaluated. Type and volume of flow were determined from a survey of commercial trucks in order to get the accident probabilities for individual routes. A population risk factor was defined as the multiplicative product of HM accident probabilities and population-at-risk in the evacuation distance. The risk score for individual routes reflected the interaction of four variables -the number of hazardous events that have occurred on the route, HM accident probability, population-at-risk and the potential hazard rating (PHR, a composite index incorporating potential incident severity) and volume of hazardous material by class.

PHR is a measure of potential hazard posed by HM transport that utilizes volume of HM by hazard class and evacuation distance by hazard class. The risk analysis for individual routes involve the use of the following equation :

$$R = H * PHR * AR * PR \qquad [2.1]$$

Where:

R = Composite risk rate on an individual route.

PHR = Potential hazard rating.

H = Number of releasing accident that have occurred.

AR = Accident rate for the route.

PR = Population-at-risk from any release along route.

2.5 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. Saccomanno et al, 1990, [11], performed a study on fatality rates and hazard areas for transporting chlorine and liquefied petroleum gas (LPG) by truck. They considered instantaneous and continous 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. The fatality rates and hazard areas associated with 50 and 1 percent damage isolines are presented in Table D.1 of appendix D.

2.6 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. Harwood et al, [6], 1990, developed a truck accident rate model as a function of roadway type and area type (urban or rural) from state data on highway geometrics, traffic volume, and accidents. California state data was used in this 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. Individual roadway segments, which have relatively short average lengths were merged into longer segments. Their average daily traffic (ADT) volumes were combined using weighted average by lengths as follows:

$$[2.2] \qquad ADT_c = (ADT_1L_1 + ADT_2L_2) \; / \; (L_1 + L_2)$$

Where :

ADT_c = Average daily traffic volume on combined segments.

ADT_i = Average daily traffic on Route segment i, (i = 1,2).

L_i = Length of Route segment i, (i = 1,2).

The truck volume data were used with the length of the segment to compute the annual vehicle-miles (veh-mi) of truck travel on each segment.

$$[2.4] \qquad TVMT_i = TADT_i * L_i * 365, \quad i = 1,2.$$

Where:

$TVMT_i$ = Annual truck travel (veh-mi) on Route segment i.

$TADT_i$ = Average daily truck volume in vehicle per day on Route segment i.

The average truck accident rate for each highway class was computed as the ratio of total truck accident to total vehicle-miles of truck travel for that highway class.

[2.4]

$$TAR_j = \sum_i \frac{A_{ij}}{VMT_{ij}}$$

Where :

TAR_j = Average truck accident rate for Highway class j.

A_{ij} = Number of accidents in one year on Route segment i in Highway class j.

VMT_{ij} = Annual vehicle-miles of travel on Route segment i in Highway class j.

2.7 METHODOLOGY TO DETERMINE SAFE ROUTES FOR HM TRANSPORTATION

A methodology has been developed by Ashtakala, 1993, [3], 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.

2.8 DISCUSSION

From the study mentioned above on designating routes for HM transportation, route designation is based on criteria selection. Any criteria such as minimize shipment distance or minimize population exposure can be selected. In this study a different approach is used in designating HM routes. The physical, chemical, and harmful properties, besides dispersion characteristics of each HM are incorporated into the risk models used in the routing process. Routes are then designated for HM of different classes for the same O-D pair. In this manner, one can investigate if they produce the same preferred routes, or if they produce separate preferred routes for each class of HM.

CHAPTER 3

THEORETICAL BACKGROUND

3.1 INTRODUCTION

The theory and concepts that are used in this study are discussed in this chapter. These concepts include, the concept of system and environment, transport of HM from origin to destination, minimum path concept and minimum exposure units, accident probability and risk. The procedures for quantifying consequences given an accident, and also for optimizing risk are discussed.

3.2 CONCEPT OF SYSTEM AND ENVIRONMENT

The system-environment ensemble exist between the transportation system and the environment. An environment may be defined as the set of all components outside the transportation system [7]. As explained in [3], traffic flow on the transportation network affect the surrounding environment. Trucks carrying HM cause damage to the road surface, and also to the surrounding population and environment in case of an accident involving the release of HM. These damages include fatalities and injuries to people, damage to plant and animal life, soil contamination, air pollution, property loss and vehicle damage.

An evacuation distance of 0.5km on each side of the road is used in case of a traffic accident involving a truck carrying HM. The number of people affected by a HM traffic accident is confined to the evacuation area adjacent to the road section. However, a HM traffic accident can cause environmental damage in the area adjacent to the road section.

3.3 TRANSPORT OF HM FROM ORIGIN TO DESTINATION

Hazardous materials are either solids, liquids or gases. An accident may occur during their transportation from the place of origin to the place of destination in which there is release of HM. Spillages of gases, liquids and solids differ from each other [4]. The area on which these spillages occur are called hazard areas and the population on these areas will be affected. Similarly, the environment will also be affected.

Gases under pressure will, if containment is lost, disperse to the surrounding atmosphere until pressure of burst container equal to the atmospheric pressure. During and after release, they mix with the atmosphere by turbulence and diffusion.

Liquids on loss of containment depend much upon whether they are stored at a temperature below or above their boiling point at atmospheric pressure. If stored at a temperature below their atmospheric-pressure at boiling point, the liquid will escape at a rate governed by the hydrostatic head available, by the size and shape of the rupture, and by the flow properties of the liquid. Liquids stored at a temperature above their atmospheric-pressure at boiling point will escape from containers at a rate that is governed by the excess pressure plus the hydrostatic head.

Solids are more complex than liquids. In some cases, solids can be scattered by localized exlposions and in some cases, it may be scattered by the loss of containment during transit.

3.4 MINIMUM 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.

A minimum path is a path with the minimum amount of a specific impedence between the O-D pair. A minimum 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 on it.

3.5 ACCIDENT PROBABILITY

The probability of a HM accident is computed from the following equation [6]:

$$[3.1] \qquad P(A)_i = AR_i * L_i$$

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 accurs. The probability of a releasing accident is computed using the following equation which replaces equation [3.1] :

$$[3.2] \qquad P(R)_i = TAR_i * P(R/A)_i * L_i$$

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 segment 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.

Equation 3.2 is more appropriate for HM routing analyses than equation 3.1 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.

Equation 3.2 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 Quebec. 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 on Table D.2 of appendix D.

3.6 RISKS INVOLVED IN THE TRANSPORTATION OF HM

Risk is defined in a conventional manner as :

[3.3] Risk = (Accident Probability) * (Accident Consequences)

The concept of accident probability is treated in section 3.5. In order to establish the accident probability of a road segment, data such as, the Annual Average Daily Traffic (AADT) volume [16], percentage of trucks [8], length and releasing accident rate for the road segment are essential.

For each spill, the consequent damages are estimated in terms of impact propagation relationships. For different types of hazardous materials, the corresponding hazard area is affected by release rates and volumes, duration of release, material properties, and meteorological conditions. Consequent damages are expressed only in terms of immediate impacts. Immediacy here refers to damages that are sustained during the duration of the spill before any containment or cleanup action. In this aspect, the long-term effects of dangerous goods spills, such as carcinogenic effects are ignored.

Consequences of HM accidents are obtained from dispersion models which are specific for each type of HM. The dispersion models give the plume size, shape, direction of movement of HM, the hazard area, volume of soil contaminated, etc. The consequences are obtained as the number of people at risk and/or the number of units of environmental components at risk in the hazard area.

Risk is then estimated as the accident probability for the road segment multiplied by the consequences. It is expressed in the number of fatalities, injuries, and units of damage to environmental components (ecology, soil, water)

3.6.1 Formulation of Risk Model

The risk model can be expressed in mathematical terms as follows [3]:

[3.4] $$ADT_i = AADT_i * PT_i$$

where :

ADT_i = Average daily trucks on road segment i.

$AADT_i$ = Annual Average Daily Traffic Volume on segment i.

PT_i = Percentage trucks on road segment i.

[3.5] $$\text{Veh-km}_i = ADT_i * L_i * 365$$

Where :

Veh-km_i = Vehicle-km on road segment i.

L_i = Length (km) of road segment i.

[3.6] $$\text{Acc. Prob}_i = (\text{Veh-km}_i * RAR_i) / 10^6$$

Where :

Acc. Prob_i = Accident probability on road segment i.

RAR_i = Releasing accident rate for road segment i.

[3.7] $PR_i = PD_i * HA_i$

Where :

PR_i = People at risk on road segment i.

PD_i = Population density on road segment i.

HA_i = Hazard area on road segment i.

[3.8] $Fatal_i = PD_i * Fatal/den$

Where :

$Fatal_i$ = Fatalities on segment i.

Fatal/den = Fatalities per unit density.

[3.9] $R_i = Acc.Prob._i * Cons_i$

Where :

R_i = Risk on road segment i.

$Cons_i$ = Consequences of an accident on road segment i.

Sample calculations for risk to population and environmental component units is illustrated in appendix D. The same procedure of calculations is carried out for the entire network for the South Central Part of Quebec (the study region). The results for the risk to population and the risk to the environment for each link is recorded on Table A.2 of appendix A.

3.7 RISK OPTIMIZATION

Minimum paths can be found between O-D pairs using risk to population and risk to the environment as link impedences. This will result in two separate paths between the O-D pairs. One for minimum risk to population, and another for minimum risk to the environment. The objective at this point is to find one path between the O-D pair which minimizes both risk to population and risk to the environment simultaneously.

The risk for each link is normalized so that comparisons can be made with the link characterized by the largest risk, and also to bring risk to population and risk to the environment to the same units. The risk to population is normalized by dividing each risk value by the largest risk to population. Similarly, the risk to environment is normalized by dividing each risk value by the largest risk to the environment [9]. These normalized values are stated as normalized risk units. The normalized risk units for the study region are presented in Table A.3 of appendix A.

A number of analyses are performed using alternative criteria and criteria weights. They range from a route designation based on minimizing risk to population, to one based on minimizing risk to the environment. Three additional applications are performed in which both criteria are considered simultaneously, applying corresponding weights to each criterion, reflecting various levels of relative importance. In the first application, 75% importance is given to risk to population, while 25% to risk to the environment. In the second and third applications, 50% and 25% importance to population risk and correspondingly 50% and 75% importance to environmental risk are given. Each application yeilds a different route between the same O-D pair. The normalized risk values with the criteria weight applications are tabulated on Table A.3 of appendix A.

In order to obtain the best route on which risk is optimized, the minimum normalized risk units are plotted against the criteria weights. The best combination of relative importance of risk to population, and risk to the environment is obtained from the minimum point of the curve. The best route is then designated using these values of relative importance. This route is the route with the minimum risk between the O-D pair in consideration.

CHAPTER 4

DATABASE

4.1 INTRODUCTION

The procedure for the establishment of the database is discussed in this chapter. This is done through a series of overlays of various maps of the study area. The South Central Part of Quebec Province is chosen as the area of study. This region contains three major cities - Montreal, Sherbrooke, and Quebec City. Four link attributes are taken into consideration. These include link distance (km), population exposure units (persons), environmental components exposure units (km^2), population risk units,and environmental risk units. A flow chart for the database establishment is shown on Figure 4.1.

4.2 CODED ROAD NETWORK

A 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.

4.3 DISTANCES (km)

The highway map for this region is used to obtain the distance of each link for the entire network [15]. Only major routes were taken into consideration. The highway network is coded into links and nodes, and the distance of each link is measured. The distance for each link of the study region is recorded in Table A.1 of appendix A.

4.4 POPULATION EXPOSURE (persons)

The population exposure unit is the number of people exposed on the evacuation area on both sides of the road. An evacuation distance of 0.5km on each side of the road is used, giving an evacuation width of 1.0km. The evacuation width multiplied by the length of the link gives the avacuation area of the link. The population density multiplied by the evacuation area gives the number of persons exposed on the link. The population densities along the links is obtained from a demographic map. The census tract division map for the region was used to obtain the demographic map [20]. This map divides the region into smaller regions and municipalities. The area and population of each region or municipality are obtained from a publication by Statistics Canada [17]. Dividing the population of each region by its area gives its population density. This is done for all the municipalities resulting into a demographic map for the region of study.

The weighted average population density by length is used in cases where the link passes through regions with different population densities. The weighted average population density is calculated from the following formula :

$$P_{WA} = \frac{\sum_{i=1}^{n} P_i L_i}{\sum_{i=1}^{n} L_i}$$

Where :

P_{WA} = Weighted average population density on link (pers/km^2)

P_i = Population density for region i (pers/km^2)

L_i = Length of link in region i (km)

The highway map is overlaid on the demographic map. Population densities corresponding to each link of the highway system is recorded in the database, Table A.1 of appendix A.

4.5 ENVIRONMENTAL COMPONENTS EXPOSURE UNITS (km^2)

The environmental component exposure unit is amount of environmental components exposed on the evacuation area of a link. The environmental aspects considered in this study are divided into the following components :

1) Farmland, which include land with crops or soils that are of agricultural value.
2) Fauna, which include areas with large concentrations of deer, resting and breeding grounds of ducks.
3) Lakes and rivers very close to the routes that can be affected in case of a spill.
4) Tourist, recreational and historical sites.
5) Forests.
6) Regions in which mining activities is taking place.
7) Soil contamination.

A distance of 0.5km on each side of the road section is considered as affected also, and the evacuation area is same as explained in 4.3. Environmental maps published by Hydro - Quebec [14], is used to obtain the environmental components on each link of the network. The highway map is overlaid on the environmental map, and environmental units corresponding to each link of the highway system is recorded in the database, Table A.1 of appendix A. The database covers several pages but, due to lack of space, only a few pages are presented in the appendix.

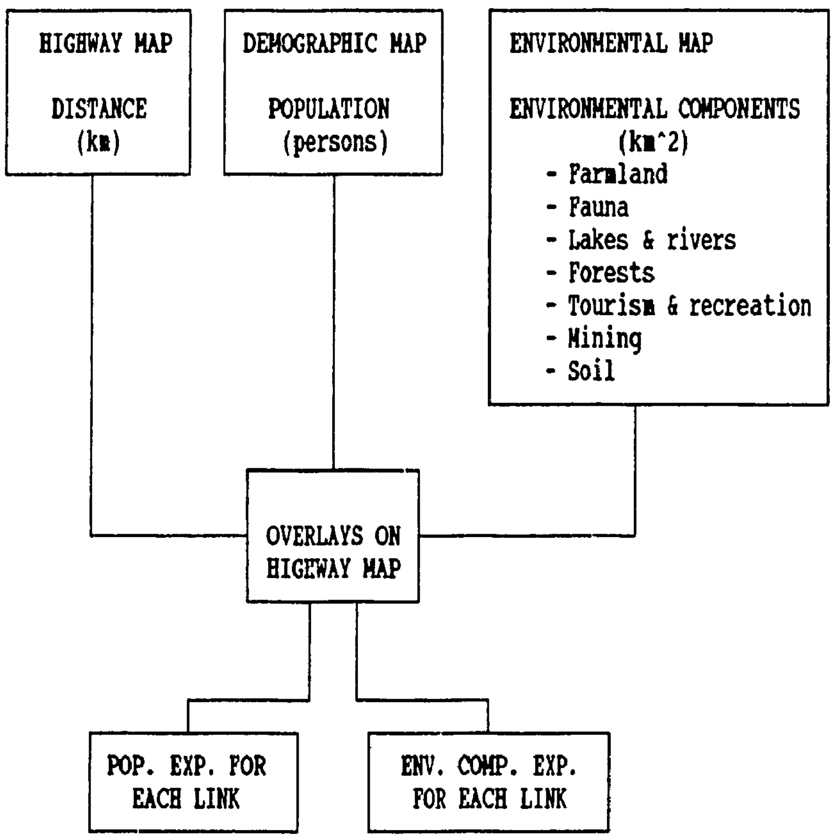


Fig 4.1 Flow chart for database.

CHAPTER 5

METHODOLOGY

5.1 INTRODUCTION

The methodology used in this study is based on the methodology given in a recent paper [3]. The methodology is modified in the risk optimization process to obtain the best route for the transportation of HM as shown in Figure 5.1. The methodology to determine minimum exposure routes, and risk optimization in the transportation of HM is made up of five stages, and each stage deals with a different aspact of the risk analysis process.

5.2 METHODOLOGY

The methodology to determine minimum exposure routes, and to minimize the consequences in case of an accident involving a truck carrying a HM is made up of the following stages.

In the first stage, 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. Other maps such as geographic, demographic, ecologic and environmental maps are overlaid on the highway map and reference points are noted on all the maps. Link attributes such as distance, population exposure, and environmental component exposure are obtained for each link on the highway network. The data corresponding to each highway link is collected from all the maps and a database is established.

The objective of the second stage, is to determine the minimum exposure routes between O-D pairs for the highway network. The minimum paths for shortest distance, minimum population exposure units, and minimum environmental components 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 minimized. Moore's algorithm (Chapter 7), is generally used for building minimum paths between O-D pairs through a coded network system. 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.

In the third stage, consequences of one HM traffic accident on each link is determined. Dispersion models which is specific for each type of HM is used. The dispersion model gives the plume size, shape, direction of movement of HM, hazard area, and volume of soil contaminated, resulting from an accident involving a truck carrying HM in which a spill occurs. The consequences is obtained as the number of people at risk, and/or the number of units of environmental components at risk which is specific for each link on the highway network.

In the fourth stage, the probability of the HM traffic accident is determined using traffic volume and accident record on each link. Accident probability, multiplied by the consequences on each link gives the amount of risk on that link. Risk is expressed as the number of fatalities, injuries and units of damage to environmental components. These risk amounts are tabulated or plotted for each link of the route between a given O-D pair.

The risk optimization process is carried out in the fifth stage. The population and environmental risk on each link of the network are normalized so that comparisons could be made with the link characterized by the largest population and environmental risk. The normalization process is carried out by dividing the risk to population and risk to environment of each link by the largest risk to population and largest risk to environment respectively [9]. A number of analysis is performed using alternative criteria and criteria weights. These range from a route designation based on minimizing risk to population, to one based on minimizing risk to environment. Several additional applications are 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 risk optimized is then designated using this combination of relative weights.

Finally, the risk amounts for various HM are tabulated for each link of a given O-D pair. The risk dissipation curves, showing how the risks will dissipate from the origin to destination point for the various HM is plotted. A spectrum of the environmental risk on these routes are also plotted. The results are used for HM planning and policy. The methodology is shown on the flow chart, Figure 5.1.

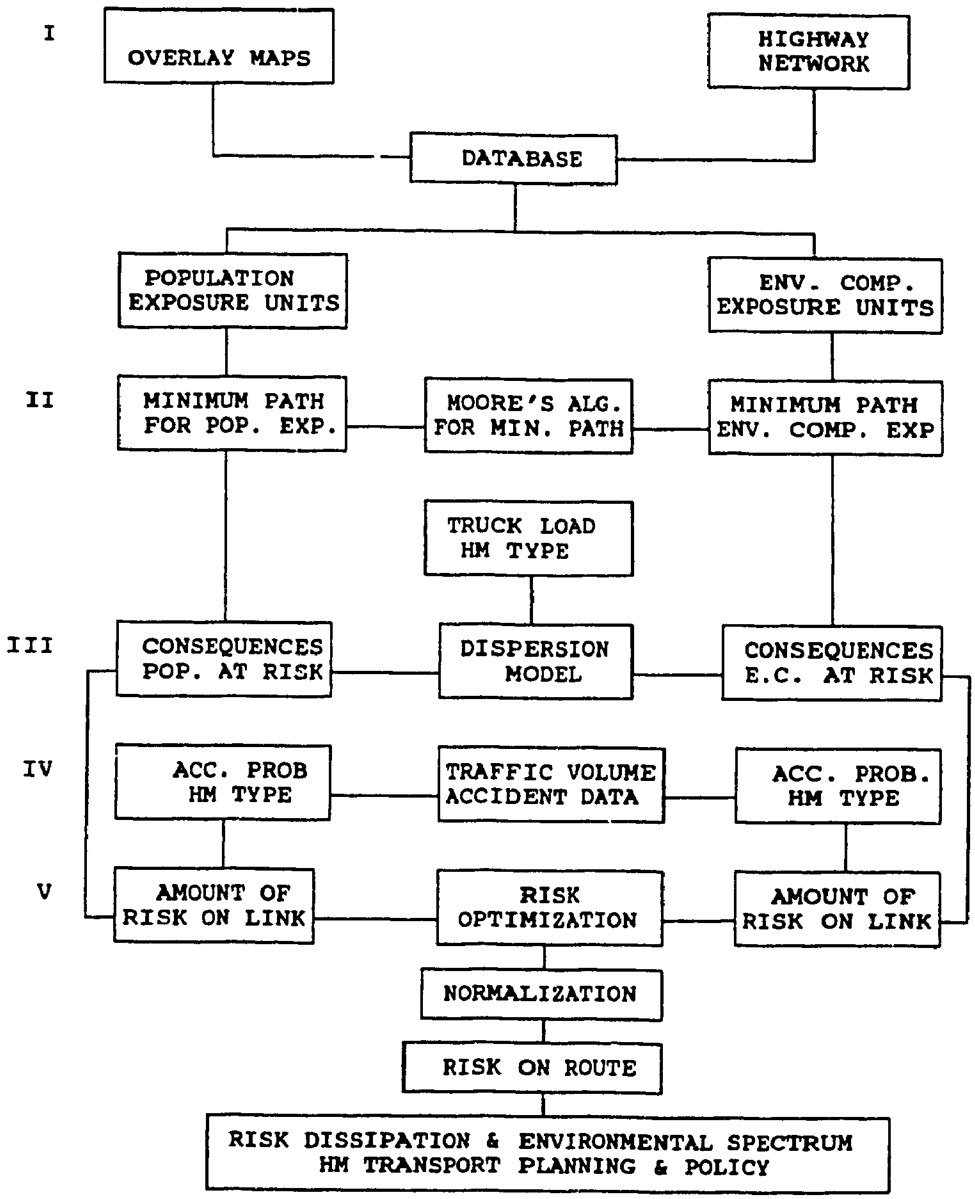


Fig. 5.1 FLOW CHART FOR METHODOLOGY

CHAPTER 6

RESULTS

6.1 INTRODUCTION

The results on the minimum exposure routes, dispersion models, and minimum risk routes is reported in this chapter. The South Central Part of Quebec Province is chosen as the study region, and eight cities in this region are the O-D pairs for this analysis. These cities include Montreal, Sorel, Drummondville, Trois-Rivieres, Victoriaville, Magog, Sherbrooke, and Quebec City. The route building algorithm used to obtain the minimum paths is based on the Moore's Algorithm. This algorithm is described ellaborately in Chapter 7.

6.2 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 are used to obtain the minimum paths. The criteria used are:

1) Minimize shipment distance (Route R1).

2) Minimize population exposure (Route R2).

3) Minimize environmental component exposure (Route R3).

Each criterion yeilded a different minimum path. The results are illustrated in the next section.

6.2.1 Minimize Shipment Distance (Route R1)

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 impedence in the route building algorithm. This resulted in the selection of routes with the minimum distance between the O-D pairs. This route is designated Route R1. The minimum distances between the O-D pairs is shown on Table 6.1.1. From the table, the minimum distance between Sherbrooke and Quebec City is 221km.

The population exposure (persons * 10^3), and the environmental component exposure (km^2) on Route R1 for the various O-D pairs are computed and tabulated on Table 6.1.2 and Table 6.1.3 respectively. From Table 6.1.2, the total population exposed on Route R1 between Sherbrooke and Quebec City is 48 * 10^3 persons, while the total environmental components exposed on this route is 34km^2 from Table 6.1.3.

Table 6.1.1: Route R1 - Minimizing Shipment Distance

Minimum Distance (km) Between O-D Pairs

TO / FROM	MTL.	SOREL	D-VILLE	T-RIV.	V-VILLE	MAGOG	SHBRKE	Q-CITY
MTL.	-	104	130	135	181	151	173	289
SOREL	104	-	61	78	117	165	142	201
D-VILLE	130	61	-	66	51	99	76	164
T-RIV.	135	78	66	-	61	165	142	123
V-VILLE	181	117	51	61	-	123	100	125
MAGOG	151	165	99	165	123	-	24	243
SHBRKE	173	142	76	142	100	24	-	221
Q-CITY	289	201	164	123	127	243	221	-

Table 6.1.2: Route R1 - Total Population Exposed on Route

(persons $*10^3$)

TO / FROM	MTL.	SOREL	D-VILLE	T-RIV.	V-VILLE	MAGOG	SHBRKE	Q-CITY
MTL.	-	264	251	173	252	249	259	291
SOREL	264	-	10	4	7	21	17	48
D-VILLE	251	10	-	6	1	15	11	43
T-RIV.	173	4	6	-	3	21	17	43
V-VILLE	252	7	1	3	-	21	17	39
MAGOG	249	21	15	21	21	-	13	52
SHBRKE	259	17	11	17	17	13	-	48
Q-CITY	291	48	43	43	43	52	48	-

Table 6.1.3: Route R1 - Total Environmental Components Exposed on Route (km²)

TO / FROM	MTL.	SOREL	D-VILLE	T-RIV.	V-VILLE	MAGOG	SHBRKE	Q-CITY
MTL.	-	61	55	36	55	54	54	55
SOREL	61	-	30	51	8	42	42	141
D-VILLE	55	30	-	34	0	34	34	0
T-RIV.	36	51	34	-	12	68	68	90
V-VILLE	55	8	0	12	-	34	34	0
MAGOG	54	42	34	68	34	-	0	34
SHBRKE	54	42	34	68	34	0	-	34
Q-CITY	55	141	0	90	0	34	34	-

6.2.2 Minimizing Population Exposure (Route R2)

The population exposure (persons) on the links of the highway network are used as the link impedence in the route building algorithm. The routes selected are routes with the minimum amount of people exposed on them between the O-D pairs. These routes are designated as Route R2. The minimum population exposed on the routes between the O-D pairs is recorded on Table 6.2.1. From this table, the minimum population exposed between Sherbrooke and Quebec City is 41 * 10^3 persons.

The distance and environmental components exposure on Route R2 for the various O-D pairs are presented on Table 6.2.2 and Table 6.2.3 respectively. The distance of Route R2 between Sherbrooke and Quebec City is 271km as indicated on Table 6.2.2, while the total environmental components exposed on this route is 23km^2 as shown on Table 6.2.3.

Table 6.2.1: Route R2 - Minimizing Population Exposure Minimum Population (persons * 10^3) Between O-D Pairs

TO / FROM	MTL.	SOREL	D-VILLE	T-RIV.	V-VILLE	MAGOG	SHBRKE	Q-CITY
MTL.	-	133	135	130	131	129	131	201
SOREL	133	-	5	4	4	13	12	42
D-VILLE	135	5	-	3	1	11	10	40
T-RIV.	130	4	3	-	3	12	11	40
V-VILLE	131	4	1	3	-	11	9	39
MAGOG	129	13	11	12	11	-	4	42
SHBRKE	131	12	10	11	9	4	-	41
Q-CITY	201	42	40	40	39	42	41	-

Table 6.2.2: Route R2 - Total Distance on Route (km)

TO / FROM	MTL.	SOREL	D-VILLE	T-RIV.	V-VILLE	MAGOG	S'BRKE	Q-CITY
MTL.	-	253	275	145	228	569	203	320
SOREL	253	-	164	78	119	466	429	232
D-VILLE	275	164	-	106	51	438	401	204
T-RIV.	145	78	106	-	74	408	371	152
V-VILLE	228	119	51	74	-	393	356	159
MAGOG	574	466	438	408	393	-	209	406
SHBRKE	203	429	401	371	356	209	-	271
Q-CITY	320	232	204	152	159	406	271	-

Table 6.2.3: Route R2 - Total Environmental Components Exposed on Route (km^2)

TO / FROM	MTL.	SOREL	D-VILLE	T-RIV.	V-VILLE	MAGOG	SHBRKE	Q-CITY
MTL.	-	130	138	24	36	59	24	86
SOREL	130	-	8	51	8	31	31	8
D-VILLE	138	8	-	12	0	23	23	0
T-RIV.	24	51	12	-	12	35	35	104
V-VILLE	36	8	0	12	-	23	23	0
MAGOG	96	31	23	35	23	-	0	35
SHBRKE	24	31	23	35	23	0	-	23
Q-CITY	86	8	0	104	0	35	23	-

6.2.3 Minimize Enviromental Components Exposure (Route R3)

For this criterion, the environmental components exposed on the links of the highway network is used as the link impedence in the route building algorithm. The routes selected are routes with the minimum amount of environmental components exposed between the O-D pairs. These routes are designated Route R3. The minimum environmental components exposed for each O-D pair is tabulated on Table 6.3.1. From this table, the minimum environmental components exposed between Sherbrooke and Quebec City is $8km^2$.

The distance and population exposed on Route R3 for the various O-D pairs is computed and tabulated on Table 6.3.2 and Table 6.3.3. The distance of Route R3 between Sherbrooke and Quebec City is 230km as shown on Table 6.3.2, while the population exposed on this route is $46 *10^3$ persons as shown in Table 6.2.3.

Table 6.3.1: Route R3 - Minimizing Env. Comp. Exp. (km^2)
Minimum Env. Comp. Exp. Between O-D Pairs

FROM \ TO	MTL.	SOREL	D-VILLE	T-RIV.	V-VILLE	MAGOG	SHBRKE	Q-CITY
MTL.	-	8	0	0	0	0	0	0
SOREL	8	-	8	8	8	16	16	8
D-VILLE	0	8	-	0	0	8	8	0
T-RIV.	0	8	0	-	0	8	8	0
V-VILLE	0	8	0	0	-	8	8	0
MAGOG	0	16	8	8	8	-	0	8
SHBRKE	0	16	8	8	8	0	-	8
Q-CITY	0	8	0	0	0	8	8	-

Table 6.3.2: Route R3 - Total Distance on Route (km)

FROM \ TO	MTL.	SOREL	D-VILLE	T-RIV.	V-VILLE	MAGOG	SHBRKE	Q-CITY
MTL.	-	270	203	490	254	178	202	367
SOREL	270	-	66	315	117	347	274	223
D-VILLE	203	66	-	287	51	281	208	195
T-RIV.	490	315	287	-	222	395	322	125
V-VILLE	254	117	51	222	-	205	132	126
MAGOG	178	347	281	395	205	-	24	303
SHBRKE	202	274	208	322	132	24	-	230
Q-CITY	367	223	195	125	126	303	230	-

Table 6.3.3: Route R3 - Total Population Exposed on Route (persons * 10^3)

TO / FROM	MTL.	SOREL	D-VILLE	T-RIV.	V-VILLE	MAGOG	SHBRKE	Q-CITY
MTL.	-	273	266	291	268	263	275	318
SOREL	273	-	6	29	7	23	19	42
D-VILLE	266	6	-	27	1	17	13	40
T-RIV.	291	29	27	-	26	37	33	48
V-VILLE	268	7	1	26	-	20	16	39
MAGOG	263	23	17	37	20	-	13	50
SHBRKE	275	19	13	33	16	13	-	46
Q-CITY	218	42	40	48	39	50	46	-

6.2.4 Detailed Illustration

In this section, a detailed illustration of the minimum path between one O-D pair is presented. The O-D pair chosen for this illustration is from Sherbrooke to Quebec City. Sherbrooke is node 45, while Quebec City is node 8.

The results for Route R1 is illustrated on Table 6.4. For link number 1, from node 45 to node 44, the distance is 5km, the population density is 74 persons/km^2, the population exposed is 370 persons, and the environmental components exposed on this link is zero km^2. From the table, from node 45 to node 8, the total distance is 221km, the total population exposed is 47971 persons, and the total units of environmental components exposed on this route is 34km^2.

Example Calculation.

The evacuation distance on each side of the road considered is 0.5km, and the evacuation width for the road section is 1km. For each 1km distance on the link, the area exposed is 1km^2. From node 45 to node 44, distance of 5km, and population density of 74 persons/km^2;

population exposed = (area exposed/km distance * link distance * population density)

$$= 1km^2/km * 5km * 74 \text{ persons}/km^2$$

$$= 370 \text{ persons.}$$

From node 44 to node 62, a distance of 34km;

environmental components exposed = (area exposed/km distance * link distance with environmental component)

$$= 1km^2/km * 34km$$

$$= 34\ km^2.$$

The detailed results for Route R2 is shown on Table 6.5. As an example, for link number 5, from node 1 to node 2, the distance is 23km, the population density is 13 persons/km², the population exposed is 299 persons, and the environmental components exposed on this link is 23km².

Detailed results for Route R3 is shown on Table 6.6. For link number 1, from node 45 to node 43, the distance is 6km, population density is 74 persons/km², population exposed is 444 persons, and the environmental components exposed is zero km². The total distance from Sherbrooke to Quebec City for Route R3 is 230km, total population exposed is 45882 persons, and the total environmental components exposed is 8km².

Detailed results and similar tables for other O-D pairs is listed in section A of appendix B. A trace of the minimum paths for the Sherbrooke to Quebec City O-D pair is illustrated on Fig. 6.1.

O-D : Sherbrooke - Quebec City

Table 6.4: Route R1 (minimizing shipment distance)

LINK NO.	NODE FROM	NODE TO	DIST. (km)	POPULATION (pers/km²)	POPULATION (persons)	ENV. COMP. (km²)
1	45	44	5	74	370	0
2	44	62	34	20	680	34
3	62	39	50	22	1100	0
4	39	38	6	1332	7992	0
5	38	17	88	25	2200	0
6	17	16	12	77	924	0
7	16	15	3	206	6183	0
8	15	14	4	849	3396	0
9	14	12	5	849	4245	0
10	12	11	4	1889	7556	0
11	11	10	4	1889	7556	0
12	10	8	6	1889	11334	0
TOTAL	-	-	221	-	47971	34

O-D pair: Sherbrooke - Quebec City

Table 6.5: Route R2 (minimizing population exposure)

LINK NO.	NODE FROM	NODE TO	DIST. (km)	POPULATION (pers/km²)	POPULATION (persons)	ENV.COMP. (km²)
1	45	43	6	74	444	0
2	43	42	54	10	540	0
3	42	41	26	6	156	0
4	41	1	72	11	792	0
5	1	2	23	13	299	23
6	2	3	21	85	1785	0
7	3	17	32	47	1504	0
8	17	16	12	77	924	0
9	16	15	2	206	412	0
10	15	14	4	849	3396	0
11	14	12	5	849	4245	0
12	12	11	4	1889	7556	0
13	11	10	4	1889	7556	0
14	10	8	6	1889	11334	0
TOT	-	-	271	-	40943	23

O-D pair: Sherbrooke - Quebec City

Table 6.6: Route R3 (minimizing enviromental component exposure)

NODE NO.	NODE FROM	NODE TO	DIST. (km)	POPULATION (pers/km²)	POPULATION (persons)	ENV. COMP. (km²)
1	45	43	6	74	444	0
2	43	42	54	10	540	0
3	42	40	8	10	80	8
4	40	2	83	31	2573	0
5	2	3	21	85	1785	0
6	3	4	31	179	5549	0
7	4	5	3	206	618	0
8	5	15	1	206	206	0
9	15	14	4	849	3396	0
10	14	12	5	849	4245	0
11	12	11	4	1889	7556	0
12	11	10	4	1889	7556	0
13	10	8	6	1889	11334	0
TOTAL	-	-	230	-	45882	8

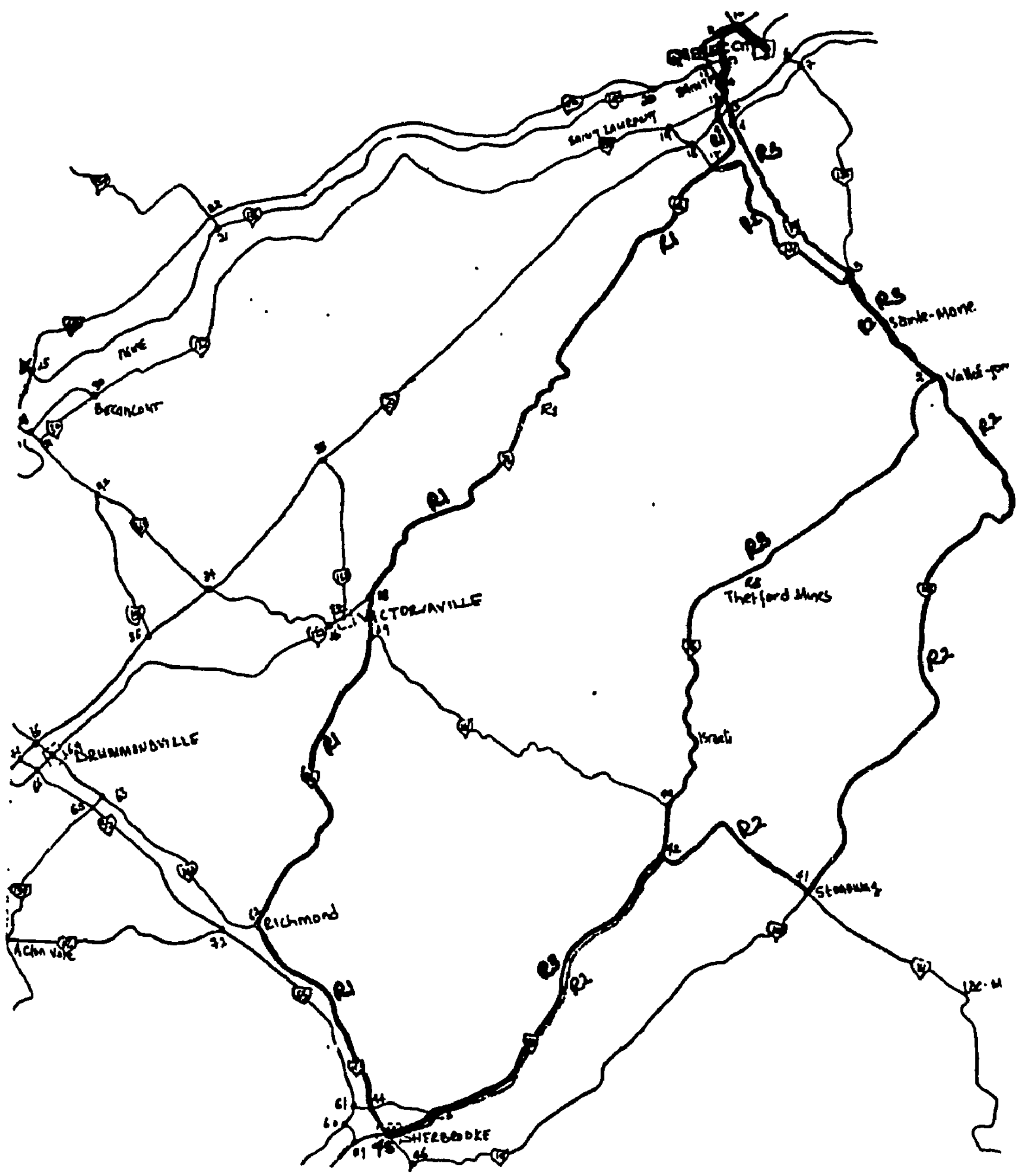


FIGURE 6.1 MINIMUM EXPOSURE PATHS (Sherbrooke - Quebec City)
Route R1 - Minimize distance
Route R2 - Minimize population exposure units
Route R3 - Minimize environmental components exposure units

6.3 DISPERSION MODELS RESULTS

The dispersion models used in this study were developed by the Institute for Risk Research at University of Waterloo [19]. The size of any hazard area is determined from dispersion models associated with each spill. Spill dispersion by propagation in the air, in rivers, in lakes, and in the soil is considered for the chemicals using a combination of site and commodity-specific parameters. The resulting impacts on human health, and the environment are represented as contours within which given toxicity, heat flux or shock wave pressure thresholds are exceeded. These contours can then be used to assess damage based on population and environmental components exposure.

Three types of HM from different class are considered for this study. Classification of HM in Canada is listed in appendix D. These HM are:

1) Chlorine Gas (Class 2 HM),
2) Liquefied Petroleum Gas (LPG, Class 3 HM),
3) Sulphuric Acid (Class 8 HM).

In this section, the hazard types, durations, and hazard areas of the dispersion models for these HM are presented. The spill model flow charts, explanations, and sample input data are presented in Chapter 7. Spill model equations, computer listings and output for LPG are listed in appendix C. Due to lack of space, similar results for chlorine and sulphuric acid are not included.

6.3.1 Chlorine Gas

Chlorine is shipped as a liquefied gas under pressure. If containment is breached, a large portion of the release will spontaneously flash-off as vapour, which will subsequently disperse in the air. The remaining portion may contaminate rivers or lakes and the soil.

The results of the dispersion of chlorine in the air, river, and lake for different types of hazard is presented below.

CHLORINE DISPERSION IN AIR

HAZARD TYPE	HAZARD AREA (km^2)	DURATION (hrs)
Fatal after a few breaths	6.3	0.24
Death in 30 minutes	7.0	0.26
Pulmonary Edema in 30 minutes	12.8	0.74
Tolerance limit for 30 to 60 min	82.1	2.23

CHLORINE DISPERSION IN RIVER

HAZARD TYPE	HAZARD DIS. (km)	HAZ. AREA (km^2)	DURATION (hours)
Aquatic life killed	0.33	16.66	0.09
50% aquatic life killed	14.81	740.40	4.11
4 day median lethal toxicity	133.27	6663.56	37.02

CHLORINE DISPERSION IN LAKE

HAZARD TYPE	HAZARD RADIUS (km)	SUR. AREA(km^2)
Aquatic life killed	0.08	0.02
50% aquatic life killed	0.21	0.13
4 day median lethal toxicity rating	0.36	0.40

6.3.2 Liquefied Petroleum Gas (LPG)

LP-gases are shipped as compressed liquids because of their high gas-to-liquid ratios. A breach of pressurized containment will result in a spontaneous flash-off of vapour and a release of cooled liquid. Immediate ignition of the vapour cloud will most likely result in a flash fire or fireball, while a delayed ignition may result in a major shockwave. Ignition of the vapours above a liquid pool results in a "pool" fire, which may heat the contents of the other tanks and result in a BLEVE (Boiling Liquid/Evaporating Vapour Explosion) [19]. The results for the dispersion of LPG is presented below for the various types of hazard.

LPG DISPERSION

FIREBALL FORMATION

HAZARD TYPE	HAZARD AREA (km^2)
Blistering of bare skin	0.15
Ignition of cellulose material	0.04
1% mortality	0.04
50% mortality	0.03

VAPOUR CLOUD SHOCK WAVE

HAZARD TYPE	HAZARD AREA (km^2)
Injury to people;window breakage	0.081
Wooden doors damage	0.040
Damage to light partitions	0.016
Damage to brick walls	0.010
Destruction of masonary buildings	0.002

POOL FIRE

HAZARD TYPE	HAZARD AREA (km^2)
Blistering of bare skin	0.050
Ignition of cellulose materials	0.009
1% mortality	0.015
50% mortality	0.009

6.3.3 Sulphuric Acid

Sulphuric acid is shipped in non-pressurized containers as a liquid acid solution of various concentrations. The acid is relatively nonvolatile (except oleum), therefore, it doesn't release hazardous vapours under normal conditions. Spill consequences include contamination of surrounding lakes, rivers and soil. The results for the dispersion of sulphuric acid for the different types of hazards is presented below.

Sulphuric Acid Dispersion

SULPURIC ACID DISPERSION IN RIVER

HAZARD TYPE	HAZ. DIS. (km)	HAZ. AREA (km^2)	DURATION (hours)
Aquatic life killed	0.1	6.5	0.04
2 day median lethal toxicity	0.6	32.1	0.18
4 day median lethal toxicity	13.0	650.7	3.62

SULPURIC ACID DISPERSION IN LAKE

HAZARD TYPE	HAZ. DIS. (km)	HAZ. AREA (km^2)
Aquatic life killed	0.06	0.01
2 day median lethal toxicity rating	0.09	0.03
4 day median lethal toxicity rating	0.20	0.13

SULPHURIC ACID FLOW IN SOIL

SOIL TYPE	DEPTH in SOIL (m)	VOLUME of SOIL (m^3)
Coarse sand	3.05	525.03
Silty sand	0.31	52.50
Clay till	0.0003	0.05

6.4 RISK OPTIMIZATION

The risk to population and environmental components for each link of the entire highway network is calculated using the risk model. Sample risk calculations is presented in appendix D. The risk is expressed in the number of fatalities, and/or units of damage to environmental components. The results for the risk to population and the risk to the environment for each link of the highway system for the study region (South Central Part of Quebec Province) is recorded on Table A.2 of appendix A. Due to lack of space only a few pages of the results are presented.

Minimum risk routes (paths with minimun risk) between the O-D pairs are selected using the route building algorithm. The risk to population (fatalities) and risk to the environment (volume of soil contaminated) are used as link impedences to obtain the minimum risk routes. As explained in chapter 3, in order to obtain one path that simultaneously minimizes risk to population and risk to the environment (optimizing total risk), the risks are normalized. The normalized risk units are then used as link impedences to obtain the minimum paths.

A number of analysis are performed using alternative criteria and criteria weights. These ranged from a route designation based on minimizing risk to population, Route R4, (100% importance to risk to population) to one based on minimizing risk to the environment, Route R8 (100% importance to risk to the environment). Where 75% relative importance was given to risk to population, while 25% to risk to the environment, this route is designated Route R5. Where, equal level of importance is given to both risks, 50% each, the route is designted R6. Where 25% relative importance is given to the risk to population, while 75% relative importance is given to the environmental risk, The route is designated R7. These values are tabulated on Table A.3 of appendix A. Only a few pages of these results are also presented due to lack of space.

Example Calculation

In this section, an example of how the normalization and criteria weighting process is carried out is illustrated for LPG. The risk to population (fatalities), and risk to the environment (volume of soil contaminated) on some eleven links is shown on Table 6.7.

The purpose of normalization is to bring both risks to the same units so that they can be comparable. This is done by dividing each risk value by the largest risk value in its category such as risk to population. From Table 6.7, the largest risk to population is 0.26850 fatalities and, all other risk to population values are normalized by dividing them by 0.26850 fatalities. These values are recorded under Route R4, which is 100% risk to population. For example, for link 1, normalized value is 0.02184/0.2685 = 0.08. The units of the normalized values is stated as normalized risk units. Similarly, form Table 6.7, the largest risk to the environment is $0.112m^3$ of soil contaminated. All the other risk values are normalized by dividing them by $0.112m^3$. These values are recorded under Route R8, which is 100% risk to the environment. For link 1, the normalized value is 0.112/0.112 = 1.00. The units are also stated as normalized risk units.

In applying criteria weights, for example link 1 from Table 6.7, the normalized risk units for Route R4 is 0.08, while for Route R8, the normalized is 1.00. Then the normalized risk units for the other route are:

Route R5 - ((.75 * 0.08) + (.25 * 1.00)) = 0.31

Route R6 - ((.50 * 0.08) + (.50 * 1.00)) = 0.54

Route R7 - ((.25 * 0.08) + (.75 * 1.00)) = 0.77.

The risk values for the other links are obtained similarly.

Table 6.7: Normalization and criteria weights application

Link No	Risk Pop (Fatal)	Risk Env. (m^3 soil)	Route R4	Route R5	Route R6	Route R7	Route R8
1	0.02184	0.112	0.08	0.31	0.54	0.77	1.00
2	0.01617	0.049	0.06	0.16	0.25	0.34	0.44
3	0.02184	0.112	0.08	0.31	0.54	0.77	1.00
4	0.16065	0.063	0.60	0.59	0.58	0.57	0.56
5	0.06000	0.065	0.33	0.39	0.46	0.52	0.58
6	0.16065	0.063	0.60	0.59	0.58	0.57	0.56
7	0.26850	0.050	1.00	0.86	0.73	0.59	0.45
8	0.06417	0.035	0.24	0.26	0.28	0.29	0.31
9	0.02468	0.018	0.09	0.11	0.13	0.14	0.16
10	0.26850	0.050	1.00	0.86	0.73	0.59	0.45
11	0.01236	0.002	0.04	0.04	0.03	0.03	0.02

The same O-D pair that was used for the results on minimum exposure routes, Sherbrooke to Quebec City, is also used in this section to illustrate the results for risk optimization. The risk values for the entire network of the study region are normalized and criteria weights applied. The normalized risk units were then used as link impedences in the route building algorithm to obtain the minimum risk on each route.The minimum normalized risk units and criteria weights for Routes R4, R5, R6, R7, and R8 is tabulated on Table 6.8. From Table 6.8, for Route R7, 25% relative importance is given to risk to population while 75% relative importance is given to the risk to the environment, resulted in a minimum risk of 2.355 normalized risk units for this route.

The normalized risk values for LPG are plotted against the criteria weights to obtain the risk optimization curve shown on Figure 6.2. From the risk optimization curve, the best combination of criteria weights is 45% relative importance to population risk, and 55% relative importance to the risk to the environment. This route is designated Route R_{min}.

This criteria weights is then used to obtain the minimum risk, and minimum risk route for the HM. An investigation was carried out on how this risk will dissipate from the point of origin to the point destination of the HM on this minimum risk route. Risk to various environmental components on the minimum risk routes are also computed and plotted. In this fashion, the full environmental spectrum on the minimum risk routes can be illustrated. The results for the HMs, is presented in the sections that follow.

O-D PAIR : SHERBROOKE - QUEBEC CITY

Table 6.8: Risk Optimization

ROUTE	% RISK POPULATION	% RISK ENVIRONMENT	NORMALIZED RISK UNITS
R4	100	0	2.458
R5	75	25	2.409
R6	50	50	2.233
R_{min}	45	55	2.164
R7	25	75	2.355
R8	0	100	2.410

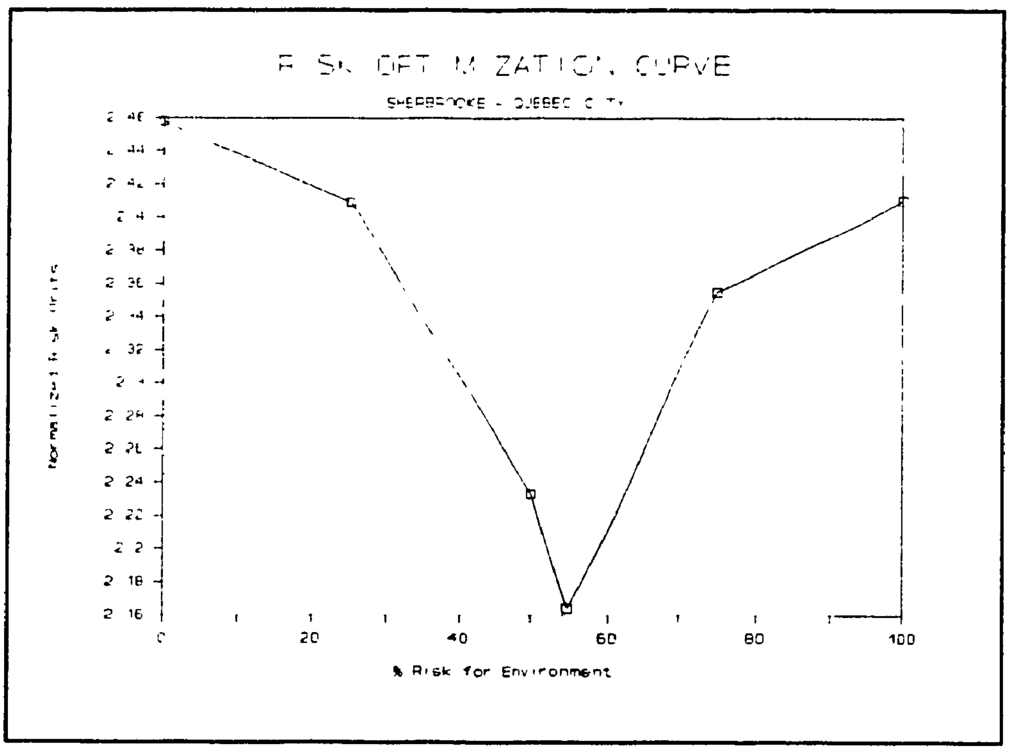


Figure 6.2: Risk Optimization Curve

6.4.1 LPG

LPG posses a threat to both population and the environment. The criteria weights obtained from the risk optimization curve, 45% relative importance to risk to population and 55% to the risk to the environment is used to obtain the minimum risk route. This route is designated Route R_{lpg}. The minimum risk obtained for this route is 2.164 normalized units. An analysis on how this risk will dissipate is illustrated on Table 6.9. As mentioned before, Sherbrooke is node 45, while Quebec City is node 8.

Risk associated with transportation of LPG from Sherbrooke to Quebec City is shown in Table 6.9. At Sherbrooke, node 45, the total risk is 2.164, risk to population is 0.887, and risk to the environment is 1.277 normalized risk units. From node 45 to node 44, a distance of 5km, the total risk dissipates to 2.139, risk to population dissipates to 0.877, and the risk to the environment dissipates to 1.262 normalized risk units. This dissipation process continues through all other nodes on the route until at the final destination, node 8, (Quebec City), where the risk is zero.

The total risk dissipation versus the distance is plotted. The total risk dissipation curve is presented on Figure 6.3, while the population risk dissipation and environmental risk dissipation curves is presented on Figure 6.4.

The risk to the environment for the minimum risk route is calculated and tabulated on Table 6.10. On this route, the risk to soil is 0.2450km^3 contaminated, and risk to fauna is 0.0280km^2 area devastated as indicated on Table 6.10. The various environmental risks versus the distances are plotted to obtain the environmental spectrum curves. The environmental spectrum curves portray the various environmental risks on the minimum risk route, and how they increase from the origin to destination. The environmental spectrum curves for Route R_{1pq} is presented on Figure 6.5.

Table 6.9: Risk Dissipation (LPG)

LINK NO.	NODE NO.	DISTANCE (km)	CUMM.DIS. (km)	T.NORM. RISK UNITS	RISK POP (norm. units)	RISKENV. (norm. units)
0	45	0	0	2.164	0.887	1.277
1	44	5	5	2.139	0.877	1.262
2	62	34	39	2.013	0.825	1.188
3	39	50	89	1.753	0.719	1.034
4	38	6	95	1.667	0.683	0.984
5	17	88	183	1.246	0.511	0.735
6	16	12	195	1.236	0.507	0.729
7	5	3	198	1.230	0.504	0.726
8	15	1	199	1.213	0.497	0.716
9	14	4	203	1.163	0.477	0.686
10	12	5	208	1.079	0.441	0.635
11	11	4	212	0.772	0.317	0.455
12	10	4	216	0.465	0.191	0.274
13	8	6	222	0	0	0

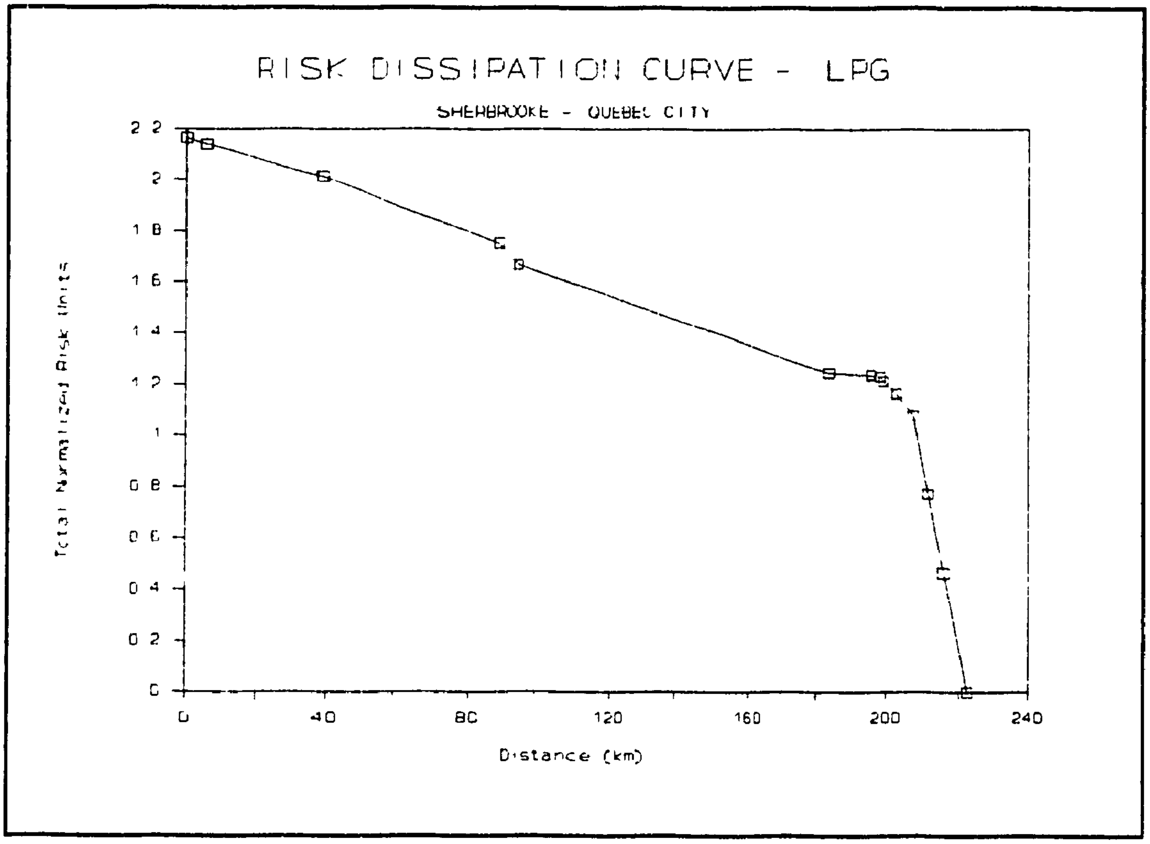


FIG. 6.3 TOTAL RISK DISSIPATION CURVE (LPG)

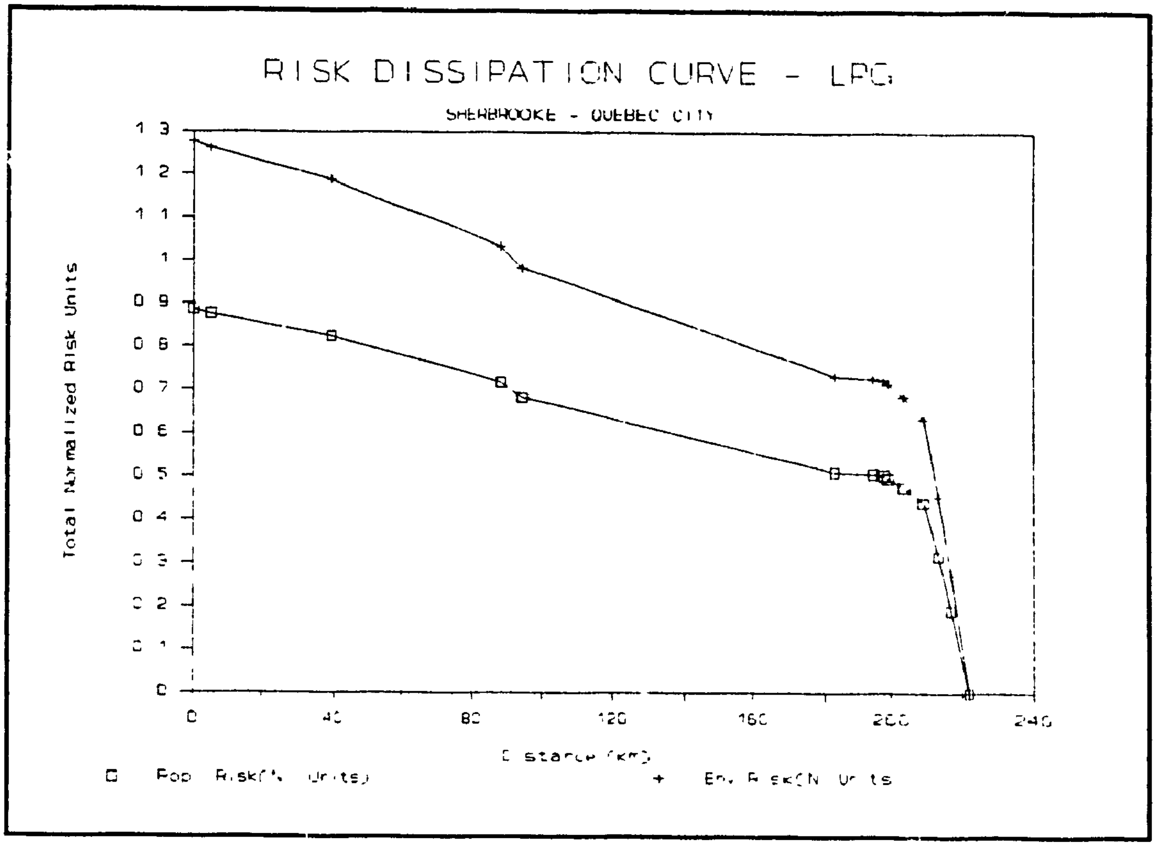


FIG. 6.4 INDIVIDUAL RISK DISSIPATION CURVES (LPG)

Table 6.10: Environmental Risk (LPG)

LINK No	Cumm. Dist. (km)	Cumm. Risk (Soil,Vol km^3)	Cumm. Risk (Fauna,Area km^2)
	0	0	0
1	5	.0045	0
2	39	.0325	.0280
3	89	.0885	.0280
4	95	.0935	.0280
5	183	.1830	.0280
6	195	.1850	.0280
7	198	.1860	.0280
8	199	.1865	.0280
9	203	.1905	.0280
10	208	.1970	.0280
11	212	.2105	.0280
12	216	.2240	.0280
13	222	.2450	.0280

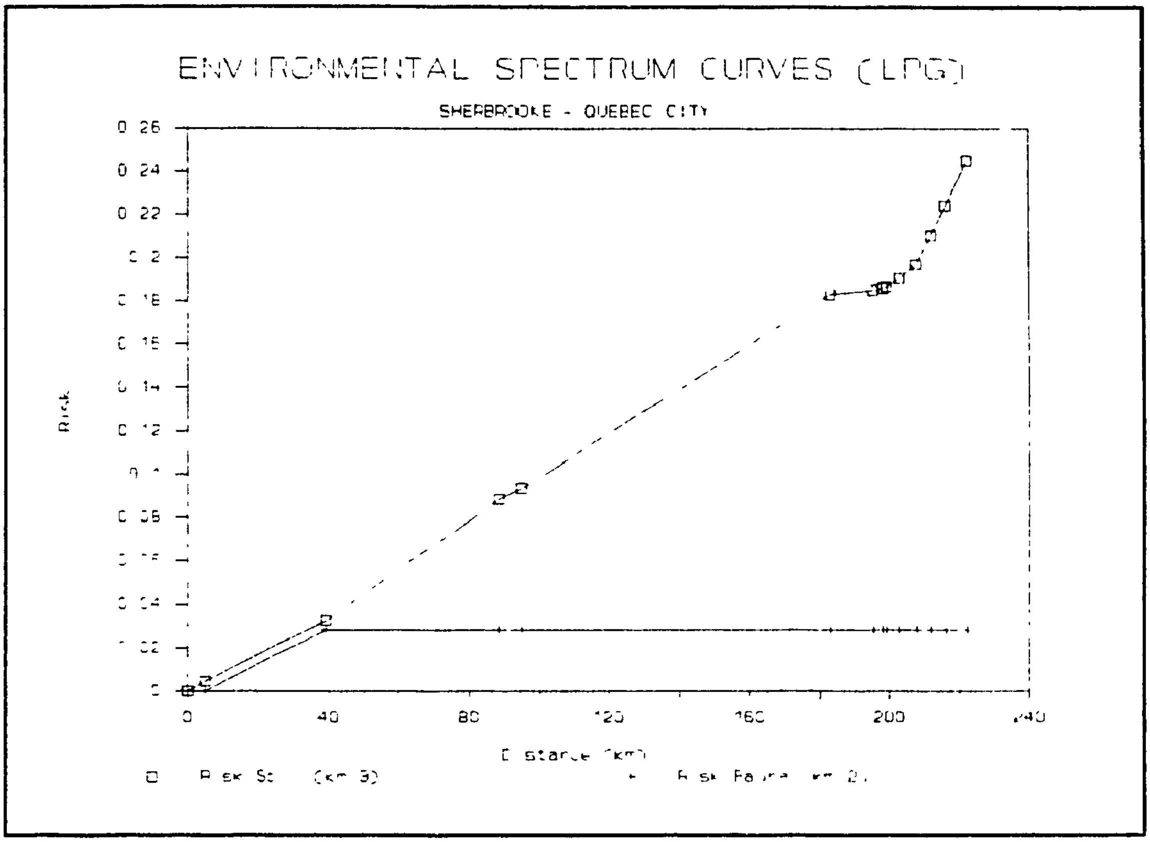


FIG. 6.5 ENVIRONMENTAL SPECTRUM CURVES (LPG)

6.4.2 Sulphuric Acid

Sulphuric acid is relatively nonvolatile, therefore it does not release hazardous vapours under normal conditions. Spill consequences are mostly environmental. The environmental risk for each link is used as the link impedence in establishing its minimum risk path. This route is designated Route R_{Acid}.

The minimum risk obtained for this route between Sherbrooke and Quebec City is 0.2425km^3 of soil contaminated. Anything on this soil such as crops, fauna and trees will be destroyed. An analysis on how this risk will dissipate is illustrated on Table 6.11. From Table 6.11, the total risk on this route is 0.2425km^3 of soil contaminated. At the origin, node 45, the risk to transport the acid to the destination, node 8, is 0.2425km^3 of soil contaminated. From node 45 to node 44, a distance of 5km, the risk dissipates to 0.2380km^3 of soil contaminated. The risk dissipates to zero at node 8 which is the final destination. The risk dissipation versus the distance is plotted to obtain the risk dissipation curve shown on Figure 6.6. From the curve, we can see that the risk dissipates uniformly from the origin to the destination.

The environmental risk on this route, Route R_{Acid} is shown Table 6.12. The risk to soil is 0.2420km^3 of soil contaminated, risk to fauna is 0.0675km^2 of their breeding area devastated, and risk to farms is 0.0530km^2 area devastated. The various environmental risks versus distance is plotted to obtain the environmental spectrum curve shown on Figure 6.7.

Table 6.11: Risk Dissipation (Sulpuric Acid)

LINK NO.	NODE NO.	DISTANCE (km)	CUMM. DIST. (km)	RISK (soilkm³)
0	45	0	0	0.2425
1	44	5	5	0.2380
2	62	34	39	0.2100
3	63	28	47	0.1930
4	64	9	76	0.1750
5	65	3	79	0.1670
6	66	33	112	0.1500
7	29	43	155	0.1125
8	28	3	158	0.1065
9	26	2	160	0.1025
10	25	9	169	0.0885
11	21	38	207	0.0700
12	20	52	259	0.0680
13	13	7	266	0.0510
14	11	8	274	0.0340
15	10	4	278	0.0205
16	8	6	284	0.0000

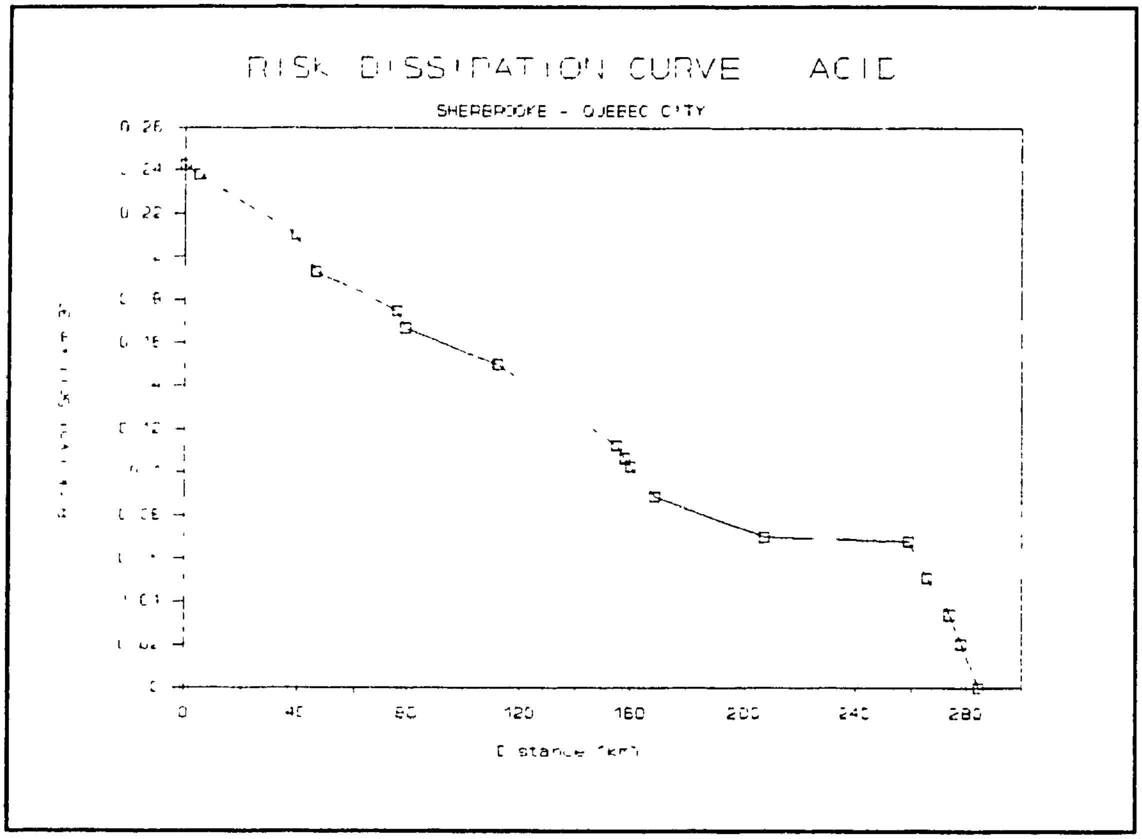


FIG. 6.6 RISK DISSIPATION CURVE (Sulphuric Acid)

Table 6.12: Environmental Risk (Sulphuric Acid)

LINK NO.	CUMM. DIS. (km)	CUMM. RISK SOIL (km^3)	CUMM. RISK FAUNA (Area km^2)	CUMM. RISK FARMS (Area km^2)
0	0	0	0	0
1	5	0.0045	0	0
2	39	0.0325	0	0
3	47	0.0495	0.0280	0
4	76	0.0675	0.0280	0
5	79	0.0755	0.0280	0
6	122	0.0915	0.0289	0
7	155	0.1290	0.0655	0.0375
8	158	0.1350	0.0655	0.0375
9	160	0.1390	0.0655	0.0375
10	169	0.1560	0.0655	0.0375
11	207	0.1715	0.0655	0.0530
12	259	0.1735	0.0675	0.0530
13	266	0.1905	0.0675	0.0530
14	274	0.2075	0.0675	0.0530
15	278	0.2210	0.0675	0.0530
16	284	0.2420	0.0675	0.0530

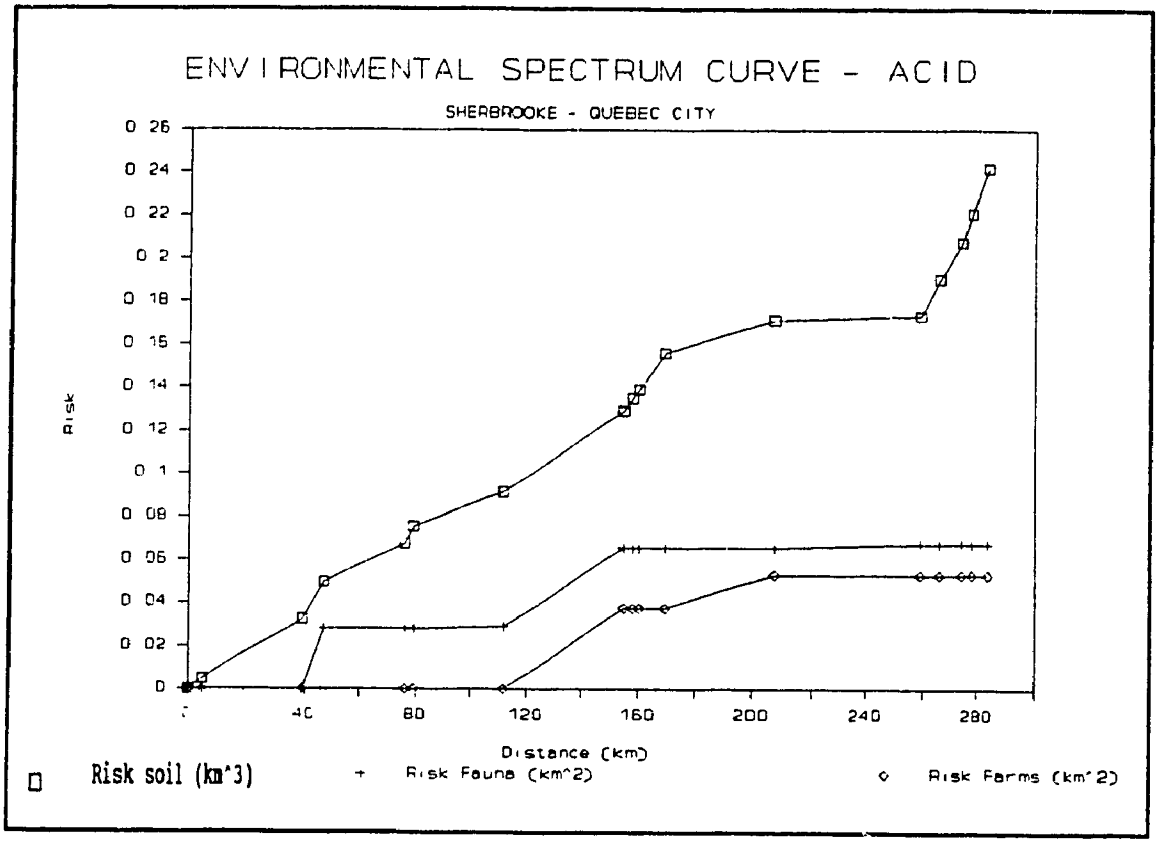


FIG. 6.7 ENVIRONMENTAL SPECTRUM CURVES (Sulphuric Acid)

6.4.3 CHLORINE GAS

Chlorine is highly lethal, and this represents its greatest threat. If a releasing accident occurs, population exposure is the link attribute that will be affected mostly. The risk to population is used as the link impedence to obtain the minimum risk route. This route is designated Route R_{c1}.

The minimum risk for this route between Sherbrooke and Quebec City is 18.272 fatalities. An analysis on how this risk will dissipate between the O-D pair is shown on Table 6.13, and the risk dissipation curve is shown on Figure 6.8.
From Table 6.14, the risk at the origin, node 45, is 18.272 fatalities. From node 45 to node 43, a distance of 6km, the risk dissipates to 18.092 fatalities, while from node 43 to node 42, the risk dissipates to 17.971 fatalities. From the risk dissipation curve, Fig. 6.8, we can notice that the risk dissipates slowly from the origin where the population density is low, and then rapidly at the end,where the population density is high.

Similar results on risk optimization for other O -D pairs for LPG, Sulphuric Acid, and Chlorine gas is shown in section B of appendix B. The traces of the minimum risk routes for LPG, Sulphuric Acid and Chlorine are illustrated on Figure 6.9.

Table 6.13: Risk Dissipation (Chlorine)

LINK NO.	NODE NO.	DISTANCE (km)	CUMM. DIST. (km)	RISK (fatalities)
0	45	0	0	18.272
1	43	6	6	18.092
2	42	54	60	17.971
3	41	26	86	17.938
4	1	72	156	17.844
5	2	23	181	17.717
6	3	21	202	17.369
7	17	32	234	17.316
8	16	12	246	17.289
9	5	3	249	17.253
10	15	1	250	17.163
11	14	4	254	16.572
12	12	5	259	15.612
13	11	4	263	11.175
14	10	4	267	6.738
15	8	6	273	0.000

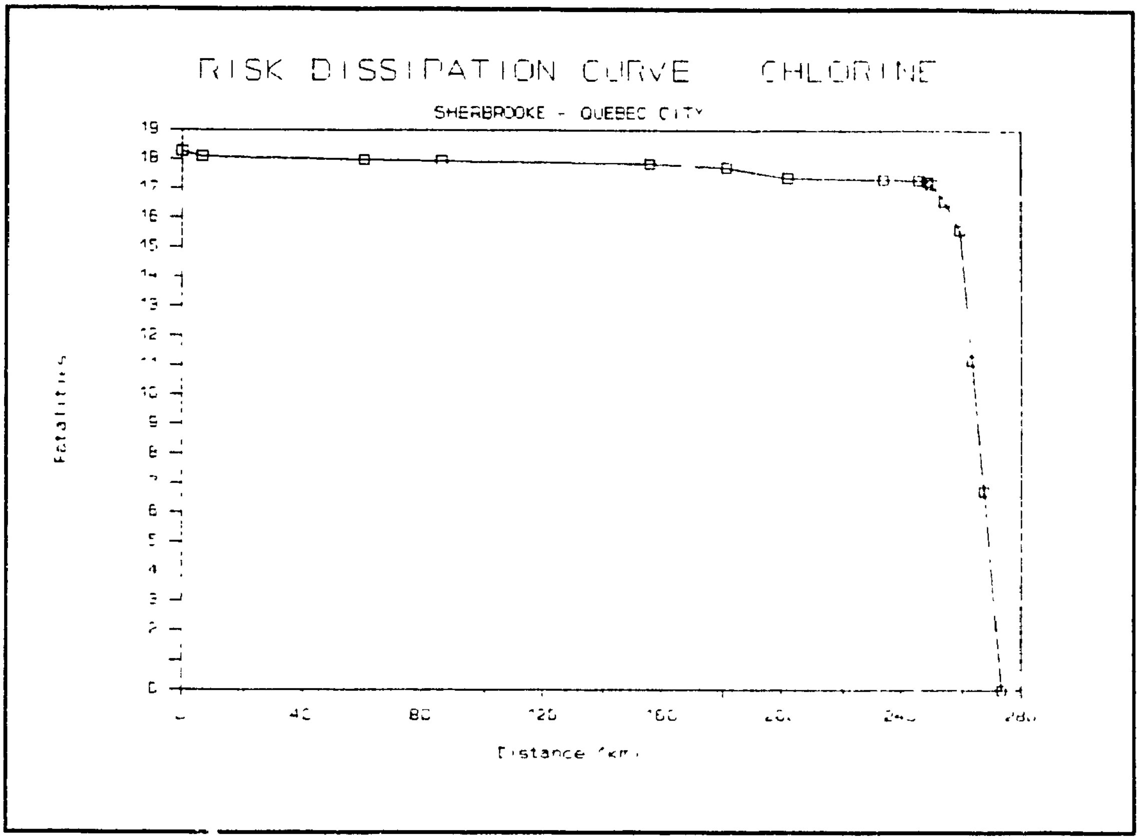


FIG 6.8 *R*ISK DISSIPATION CURVE (Chlorine)

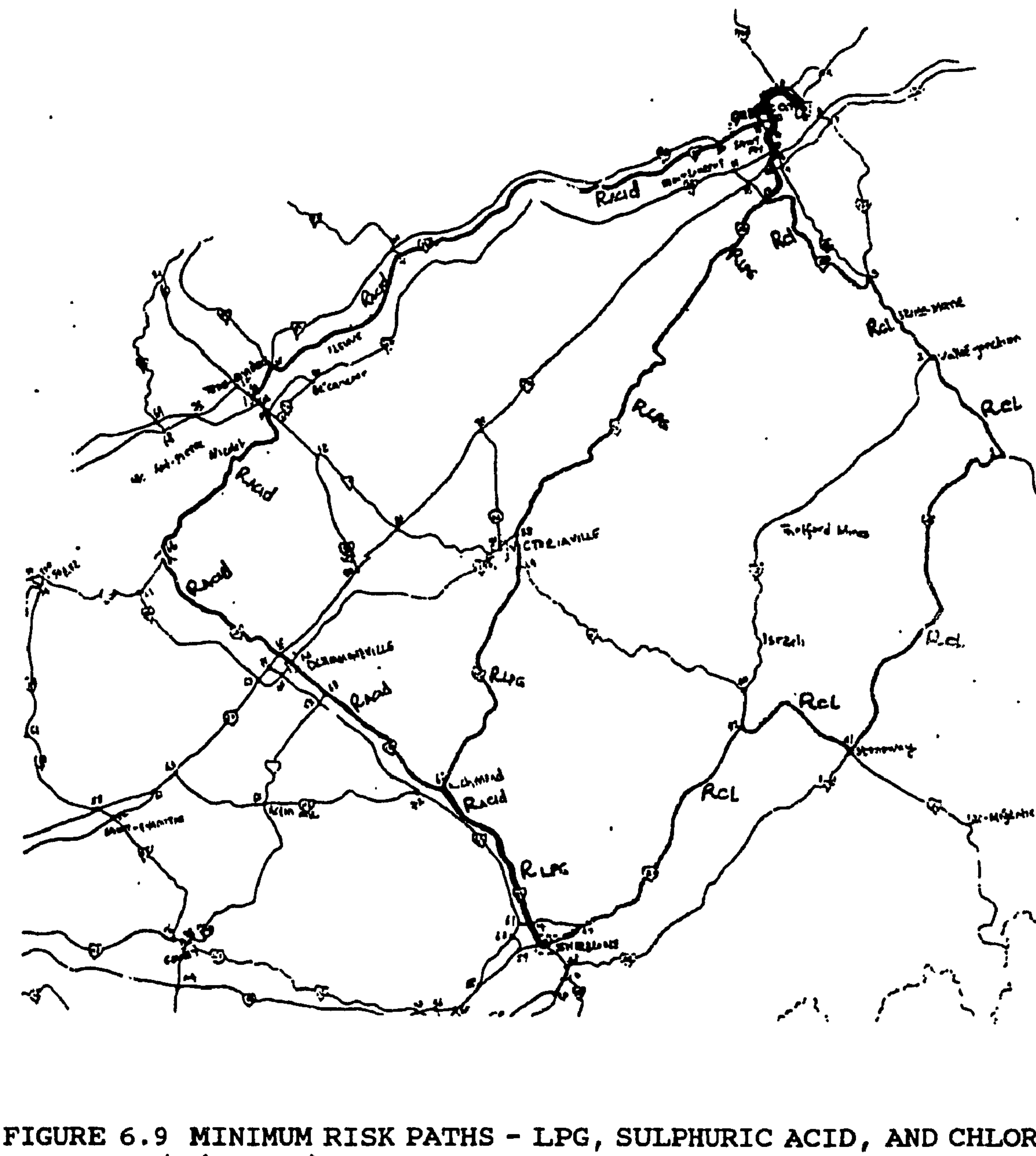


FIGURE 6.9 MINIMUM RISK PATHS - LPG, SULPHURIC ACID, AND CHLORINE

R_{LPG} - Minimum risk route LPG

R_{Acid} - Minimum risk route sulphuric acid

R_{cl} - Minimum risk route chlorine

6.5 DISCUSSION OF RESULTS

The discussion is divided into three sections. The minimum exposure routes are discussed first, followed by the dispersion models. Finally, the minimum risk routes are discussed.

6.5.1 Minimum Exposure Routes

An analysis is performed to find out how the minimum exposure routes differ from each other. Route R1 represents the route that minimizes travel distance. Route R2 represents the route that minimizes population exposure while Route R3, the route that minimizes environmental components exposure. The distance, population exposure and environmental components exposure of each route is shown on Table 6.14.

The application of different routing criteria results in the selection of different preferred routes. These different preferred routes are shown on Figure 6.1. This shows that when the criterion of minimizing population exposure or environmental components exposure is applied, a route other than shortest route by distance is selected. As noted on Table 6.14, for shipments between Sherbrooke and Quebec City, the travel distance increases from 221km (Route R1), to 271km (Route R2), a 23% increase. Comparing Route R2 with the minimum travel distance route Route R1, the population exposure decrease by 15%, and the environmental components exposure decrease by 32% for Route R2.

Table 6.14: Comparison of Routes

ROUTE	DISTANCE (km)	POPULATION (persons $*10^3$)	ENV.COMP.UNITS (km^2)
R1	221	48	34
R2	271	41	23
R3	230	46	8

6.5.2 Dispersion Models

The three HM have different dispersion models, and the hazards they cause in case of a spill are different. For chlorine gas, a spill will disperse in the air and nearby rivers and lakes. LPG spill will result in fireball formation, vapour cloud shock wave, and pool fire while, a sulphuric acid spill will disperse in nearby rivers and lakes, and also flow in soil.

The results, show that the hazards and hazard areas for these HM are different. For chlorine dispersion in air, the hazard area for the hazard - fatal after a few breaths is 6.3km^2, while the hazard area for the hazard -death in 30 minutes is 7.0km^2. For LPG spill where there is formation of pool fire, the hazard area for the hazard - blistering of bare skin is 0.050km^2, while the hazard area for the hazard - ignition of cellulose material is 0.009km^2.

Another important finding is that dispersion in the same medium for the same type of hazard, produced different hazard areas, distances, and duration for the different HM. For example, dispersion of chlorine and sulphuric acid in a river. For a hazard where aquatic life is killed, the hazard area for chlorine gas is 16.66km^2, the distance is 0.33km, and the duration is 0.09 hours. The hazard area for sulphuric acid is 6.5km^2, the distance is 0.1km, and the duration is 0.04 hours. Therefore, the dispersion of the HM are different and depend on the physical, chemical and hazard properties of the HM.

6.5.3 Minimum Risk Routes

From the results and from Figure 6.9 on which the minimum risk routes for different HM are traced, it can be observed that the different HM resulted in the selection of different preferred routes. The minimum risk on Route R_{lpg} for LPG is 2.164 normalized risk units, on Route R_{Acid} for sulphuric acid is 0.2425km^3 soil contaminated, and on R_{cl} for chlorine gas is 18.272 fatalities.

These results showed that the physical and chemical characteristics of a HM is very important in determining its hazards and risks to population and the environment. Depending on the harmful properties of the HM on population, animals, plants, rivers, lakes and the soil, different routes will be selected, minimizing the risk related to these attributes on the route.

Route designation for the transportation of HM, should be done according to HM class which is based on the physical and chemical characteristics, and hazard properties of the HM. A separate preferred route for each HM class, between the given origin - destination pair is to be selected rather than a single route for all types of HM.

CHAPTER 7

COMPUTER PROGRAMS

7.1 INTRODUCTION

The programs used in this study are written in Quick Basic programming language. These programs include program for route building algorithm, dispersion models for chlorine gas, LPG, and sulphuric acid. Explanation of how the programs work, flow charts, and sample input data are presented in this chapter. Spill model equations, program listings and output are listed in appendix C.

7.2 ROUTE BUILDING ALGORITHM

The route building algorithm is based on Moore's algorithm [7]. The transport network is coded in terms of links, nodes and centroids. For example, using distance as link impedence, for each origin centroid, the aim of this algorithm is to assign a label to each node in the network of the following form:

[7.1] node j label = [i, d(j)]

where :

i = the node nearest to zone j which is on the minimum distance path back to the origin.

d(j) = the minimum distance from node j back to the origin controid.

Initially, each node is assigned a d(j) magnitude which is a very large number, say 999, with the exception of the origin node which is set to zero. As the route is built out from the origin, the following sum is formed for each node :

[7.2] node j sum = [d(i) + l(i,j)]

where :

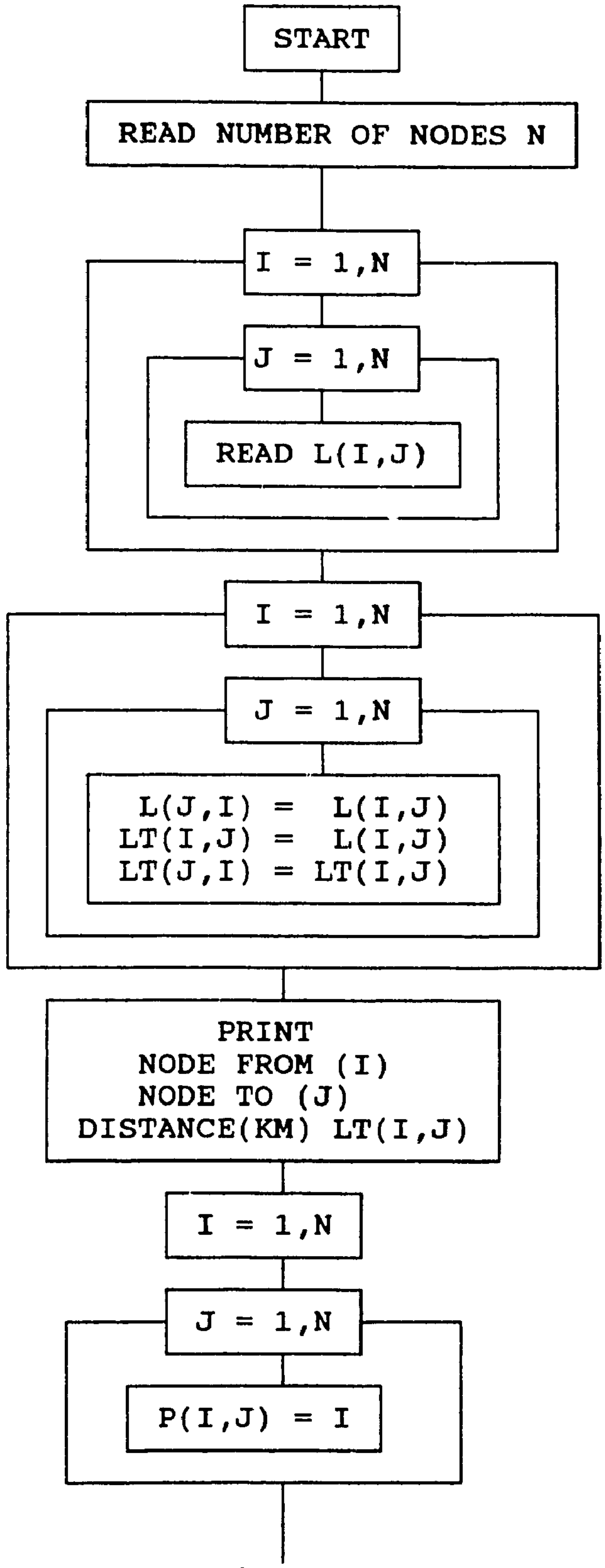
d(i) = the distance from the origin to node i which has just been connected to the origin.

l(i,j) = the distance along the link which connects node j to node i.

If the sum just formed is greater than the d(j) already recorded for node j, then the node is bypassed. If the sum is less than the existing d(j), then the d(j) is replaced by the newly formed sum and the i is changed in the label to reflect the new connecting link for node j back to the origin. New sums are formed for the nodes adjacent to the nodes just connected to the origin and these sums are tested against the d(j) magnitudes recorded for for the nodes. The process is continued untill all nodes have been reached. The label numbers for each node show the minimum distance back to the origin as well as the node which is the next nearest on the minimum path back to the origin. This building process must be carried out for each origin centroid in turn.

7.2.1 FLOYD'S ALGORITHM

Floyd-Warshall have modified the original Moore algorithm, and have produced a computationally more efficient route building algorithm using matrices. The flow chart for Floyd's algorithm is shown on Figure 7.1.



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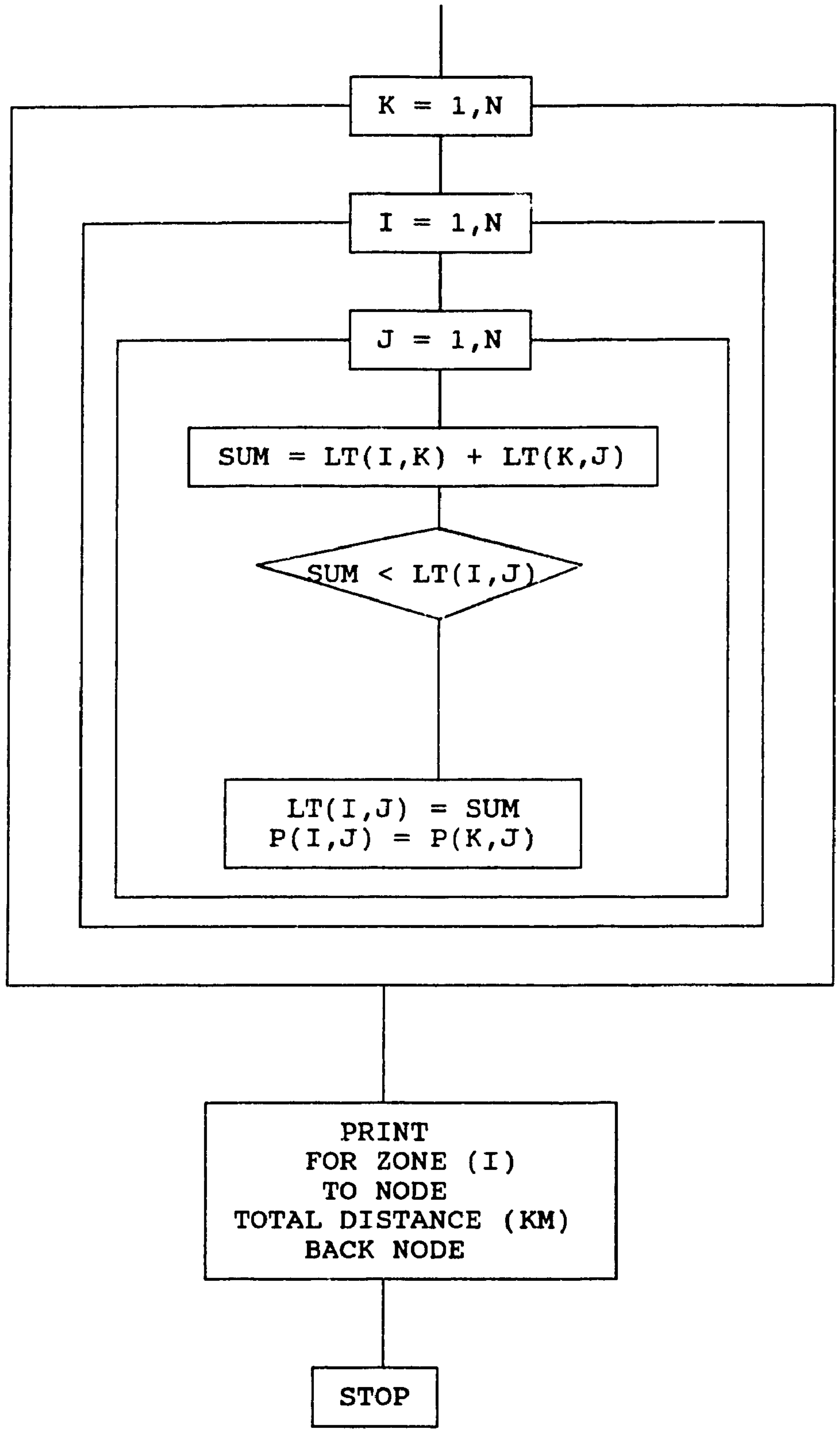

FIG. 7.1. FLOW CHART FOR ROUTE BUILDING ALGORITHM

7.2.2 EXPLANATION

The program works as follows. Having coded the study area, the number of nodes is read by the program. A skim tree matrix depicting the attribute, say distance, is read from the data file. Links that are not connected are given a value of LT(I,J) = 999 (a large number). Also LT(I,J) = zero when I = J. To keep track of the nodes that the minimum path will pass through, we use another matrix P(I,J) where P(I,J) = I for all I.

The Floyd algorithm is as follows :

SUM = LT(I,K) + LT(K,J)

? SUM <= LT(I,J) = 999

If SUM is less than 999, then

LT(I,J) = SUM and

P(I,J) = P(K,J).

IF the SUM is not less than 999, the node is bypassed. We recall that,

```
For K = 1,N     SUM = LT(I,K) + LT(K,J)
For I = 1,N     IS SUM < LT(I,J)
For J = 1,N   IF YES, LT(I,J) = SUM ; P(I,J) = P(K,J)
                IF NO, BYPASS.
```

Once the 3-D loop is done the LT(I,J) will contain the total distance for each O-D pair. The matrix P(I,J), the back node matrix will contain the nodes through which the minimum path passes. A complete computer listing, example network and printouts is presented in appendix C.

7.3 DISPERSION MODELS

The computer models for chlorine gas, LPG, and sulphuric acid are one component of the network risk analysis model developed by the Institute for Risk Research at University of Waterloo [19]. The resulting impacts are represented as contours within which given toxicity, heat flux or shock wave pressure thresholds are exceeded.

7.3.1 Chlorine Gas

The spill model estimates the fractions of a release which will contaminate the air, a nearby river and/or lake. It specifically considers instantanous release, but larger continous releases which escape over relatively short time periods can also be considered. The estimates of the quantities of chlorine released to the air or nearby rivers and lakes then become inputs to separate subroutines which estimate the resulting impact in each of these media. An overview of this process is provided in Figure 7.2.

Dispersion in air

The air dispesion model considers a large, relatively instantaneous release of chlorine into the atmosphere in the form of a puff, which is modelled as an instantaneous point source. The approach for calculating the hazard areas associated with this dispersion consists of five basic steps:

1. Calculate puff hazard half-width

2. Calculate normalized vapour concentration
3. Calculate maximum downwind hazard distance
4. Check on model validity
5. Calculate hazard area at a given threshold

Dispersion in a river

The five steps in calculating the hazard area associated with the dispersion of chlorine in a river are as follows:

1. Calculate hydraulic radius and cross-sectional area of the river
2. Calculate longitudinal diffusion coefficient
3. Calculate delta and alpha factors
4. Check model validity
5. Calculate hazard area for a given threshold

Dispersion in a Lake

The contaminated volume in a lake is modelled as a cylinder of material of uniform concentration. The radius of the cylinder is equal to the distance to a given concentration, while the length is the depth of the lake.

Some contaminants may enter the soil, but the impacts of this is not modelled at present. This is the least damaging situation in a chlorine release, considering the highly fatal effects of the vapours. The implementation of the spill model is performed using the equations listed in appendix C. Computer listings and output are also listed in appendix C.

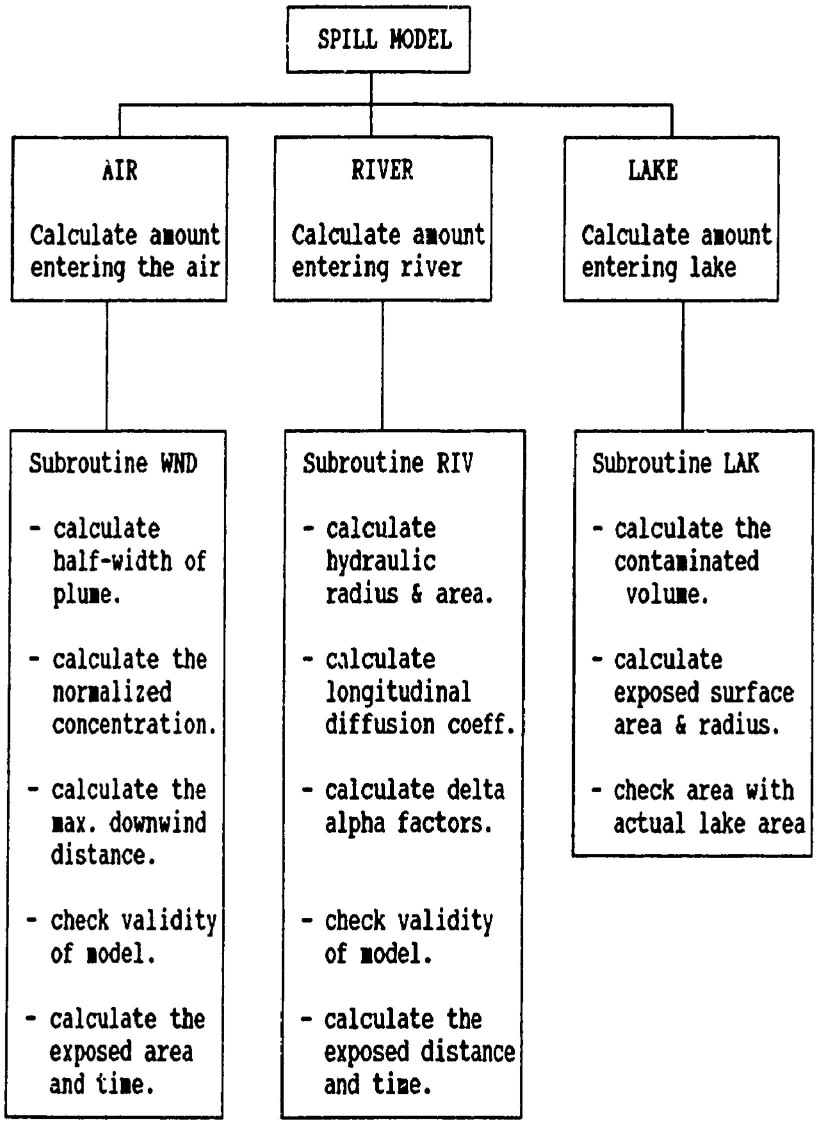

FIG. 7.2 SPILL MODEL AND SUBROUTINES (CHLORINE)

Sample Input Data (Chlorine Gas)

SAMPLE VALUE	DEFINITION OF THE INPUT VALUE

Spill Submodel Input Data

20	instantaneous quantity spilled (tonnes)
100	continuous spill rate (kg/min)
10	continuous spill time (min)
20	ambient temperature at time of spill (deg C)
1	additional fraction entrained (fraction of flash-off)
0.4	fraction of remaining liquid flowing to river
0.3	fraction of remaining liquid flowing to lake

Air Dispersion Input Data:

2.1	wind speed (m/s)
0.37	dispersion coefficient a
2.481	dispersion coefficient b
0.3818	dispersion coefficient c
2.4653	dispersion coefficient d
3	critical concentration in air 1 (g/m^3)
2.4	critical concentration in air 2 (g/m^3)
0.18	critical concentration in air 3 (g/m^3)
0.012	critical concentration in air 4 (g/m^3)

River Dispersion Input Data

50	river width (metres)
5	river depth (metres)
1	river speed (m/s)
0.5	liquid boil-off
1	liquid evaporation
20	critical concentration of chlorine in river 1 (ppm)
3	critical concentration of chlorine in river 2 (ppm)
1	critical concentration of chlorine in river 3 (ppm)
0.03	mannings "n"
0.5	boil-off fraction
1	evaporation fraction

Lake Dispersion Input Data:

5	lake depth (m)
100000	lake area (m^2)
20	critical concentration 1 (ppm)
3	critical concentration 2 (ppm)
1	critical concentration 3 (ppm)

7.3.2 Liquefied Petroleum Gas

The purpose of the spill submodel is to determine which fractions of a shipment will contribute to forming a fireball, a vapour cloud explosion, or a pool fire following an accident. It considers the size of the shipment, the prevailing environmental conditions, and those factors which may influence the expected time to ignition. An overview of the process is provided in Figure 7.3.

The amount of vapour contributing to either a fireball or vapour cloud explosion is derived from the mass spilled, multiplied by the flash evaporation fraction and an additional amount of liquid entrainment. The amount of LPG remaining as a liquid pool is determined as the difference between the amount spilled and the amount of vapour formed.

The implementation of the spill model is performed using the equations listed in appendix C. Computer listings and output are also attached in appendix C.

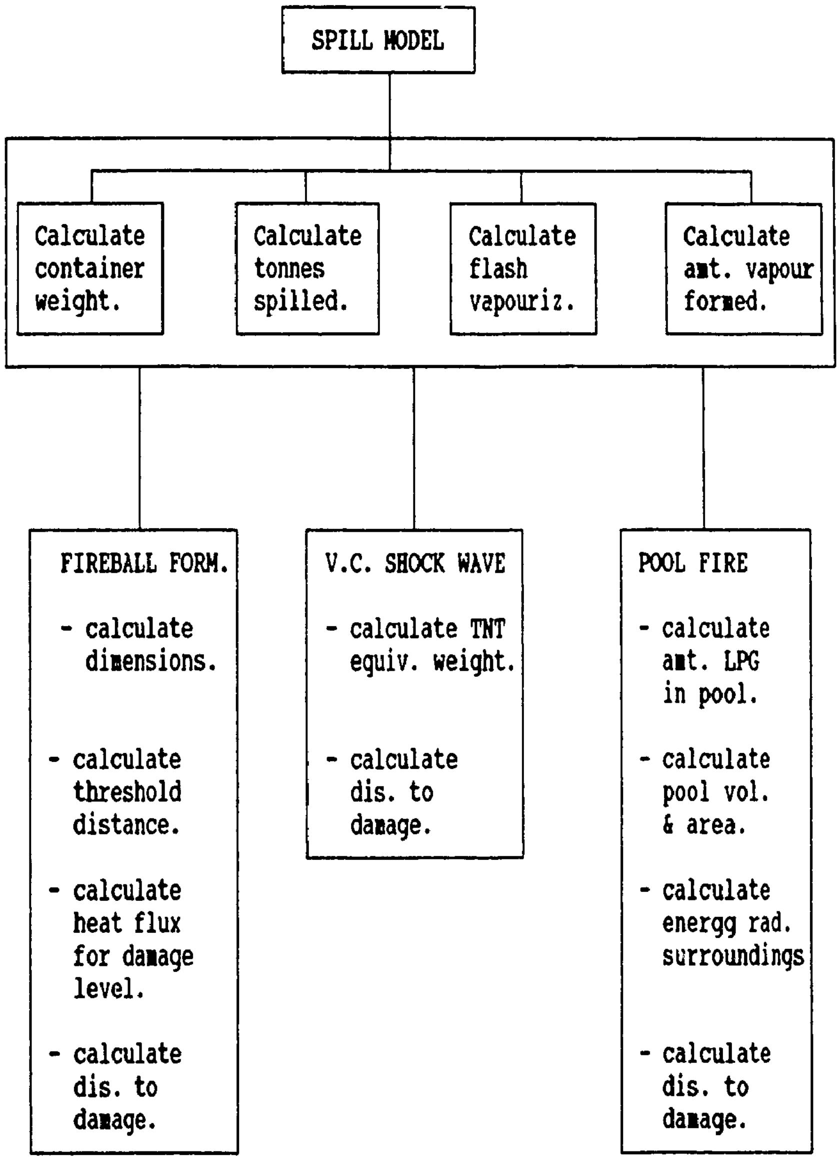

FIG. 7.3 SPILL MODEL FOR LPG

Sample Input Data (LPG)

SAMPLE VALUE	DESCRIPTION OF THE INPUT VALUE

<u>Spill Submodel Input Data:</u>

13.5	Norminal container volume (m^3)
0.85	Fraction of container filled
493.5	Density of liquid in container (kg/m^3)
1.0	Fraction of container spilled
0.1	Delay of ignition (minutes)
20	Temperature (degree celcius)
1	Entrained liquid as a percent of flashing fraction

<u>Fireball Input Data:</u>

27.5, 3.76	Fireball radius and duration coefficients
0.1, 5.67E-08, 2200	Gas emmissivity, Stephan-Boltzman constant, flame temperature (deg K)
0.3, 50340	Fraction of heat release - Roberts, Heat of combustion--CRC Handbook (KJ/kg)
-.7481, 1.751	Coefficient a and b for blistering bare skin Roberts, 1982
-.4121, 2.068	Coefficient a and b for ignition of cellulose material
-.7418, 2.266	Coefficient a and b for 1 % mortality rate
-.7498, 2.52	Coefficient a and b for 50 % mortality rate
0.1	Efficiency factor
1.196E07	Heat content propane (cal/kg) - Rose (1984)
1.106E06	Heat content TNT (cal/kg) - Rose

<u>Input Data for Vapour Cloud Shock Wave:</u>

150	C coefficient for no damage (range 50-150) - Clancy(1982)
10	C coefficient for injury to people, glass windows broken
7	C coefficient for damage to wooden doors
4.5	C coefficient for destruction of light partitions
3.5	C coefficient for collapse of brick walls in small buildings
1.5	C coefficient for destruction of stone and brick buildings

<u>Input Data for Pool Fire:</u>

2	Pool thickness
0.13	Propane burning rate (kg/m^2 s) - Mizner and Eyre (1982)
50359	Propane heat release rate (KJ/kg) - CRC Handbook
6	Blistering of bare skin in 20 seconds (kw/m^2) - Roberts
34	Ignition of cellulose materials (kw/m^2)
20	1 % mortality rate (kw/m^2)
35	50 % mortality rate (kw/m^2)

7.3.3 Sulphuric Acid

When sulphuric acid is spilled on water or land, some may flow to rivers or to lakes, and the remainder percolates through the soil. Since evaporation of even the most concentrated acid is relatively small, evaporation is not considered in this model. The spill model determines the amount of acid that disperses via rivers, lakes and soil. An overview of this process is shown in Figure 7.4.

The spill model computes the tonnage of sulphuric acid that becomes dissolved in any nearby rivers and lakes, and the tonnage that remains on the soil. Estimates of these tonnages are then used in the subroutines specific to each medium to calculate the impacts involved. Implementation of the spill model is accomplished using the equations listed in Appendix C. Computer listing, and output for thespill model for sulphuric acid is also presented in Appendix C.

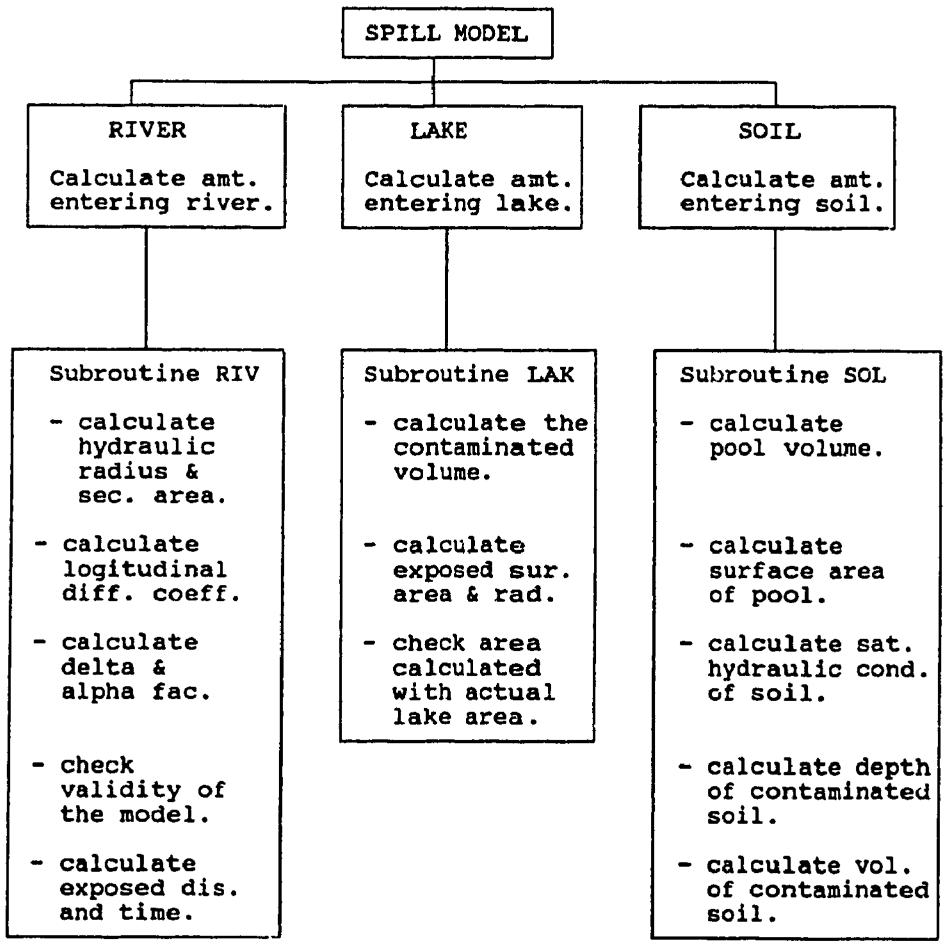

FIG. 7.4 SPILL MODEL FOR SULPHURIC ACID

Sample Input Data (Sulphuric Acid)

SAMPLE VALUES	DEFINITION OF THE INPUT VALUE

Sample Submodel Input Data:

20	instantaneous quantity spilled (tonnes)
100	continuous spill rate (kg/min)
10	continuous spill time (min)
20	ambient temperature at time of spill (deg C)
1	fraction of sulphuric acid in solution
1830	density of concentrated acid solution (kg/m^3)

River Dispersion Input Data:

50	river width (metres)
5	river depth (metres)
1	river speed (m/s)
100	#1 critical concentration of sulphuric acid (mg/l)
45	#2 critical concentration of sulphuric acid (mg/l)
10	#3 critical concentration of sulphuric acid (mg/l)

Lake Dispersion Input Data:

5	lake depth (m)
100000	lake area (m^2)
100	#1 critical concentration (mg/l)
45	#2 critical concentration (mg/l)
10	#3 critical concentration (mg/l)

Dispersion Through Soil Data:

2	pool thickness (cm)
1E-09	intrinsic permeability of coarse sand (m^2)
1E-12	intrinsic permeability of silty sand (m^2)
1E-15	intrinsic permeability of clay till (m^2)
12	time from spill to clean up (hrs)

CHAPTER 8

CONCLUSION AND RECOMMENDATIONS

This chapter summarizes the principal conclusions developed from this study, and suggests some recommendations for further research in this area.

8.1 CONCLUSIONS

The major conclusions of this study are as follows :

1) The application of different routing criteria results in the selection of different preferred routes. When the criterion of minimizing population exposure or environmental components exposure is applied, a safer route other than the shortest route by distance is selected. Less people are exposed to the dangers of a HM in case of an accident on a route designated based on minimizing population exposure units. Similarly, less environmental components are exposed on a route designated based on minimizing environmental components exposure units. These routes are safer because of their fewer exposure units.

2) The three HM, LPG, Sulphuric acid, and Chlorine gas have different dispersion models. Their hazards and hazard areas are different, depending on their physical, chemical, and hazard properties. A breach of a pressurized containment of LPG results in a spontaneous flash-off of vapour and release of liquid giving

rise to a fireball, vapour cloud shock wave or a "pool" fire. The hazards include blistering of bare skin, death, and destruction of buildings. Sulphuric acid is non-volatile and does not release hazardous vapours. Spill consequences include contamination of surrounding lakes, rivers and soil. For Chlorine gas, if containment is breached, a large portion of the release will spontaneously flash-off as vapour, which will disperse in the air. The remaining portion may contaminate rivers or lakes. Therefore, each HM is unique in causing dangerous consequences to population and the environment.

3) The different HM resulted in the selection of different preferred routes. The physical and chemical characteristics of a HM is very important in determining its hazards and risks to population and the environment. LPG affects both population and the environment. Sulphuric acid mostly affects the environment, while Chlorine gas mostly affects population. Thus depending on the harmful effects of the HM on population and the environment, different routes are selected, minimizing the risks on the preferred route.

4) A method to combine population risk and enviromental risk and, a technique has been developed to find a route between an O-D pair that simultaneously minimizes both population and environmental risks. This is the risk optimization technique. Both population and environmental risks are normalized, criteria

weights are applied and varied until a combination of criteria weights with minimum risk is obtained. This combination of criteria weights is then used to determine the minimum risk route between the O-D pair which simultaneously minimizes both population and environmental risk.

5) At the origin of any trip, the total risk is maximum. The total risk will gradually dissipate to zero at the end of the trip.This is illustrated on the risk dissipation curve. This curve gives an indication of which sections of the road are more vulnerable to damage and, which sections are less vulnerable to damage in case of an accident. The dissipation rate for more vulnerable sections is higher, while the dissipation rate for less vulnerable sections is lower.

6) The environmental components on each route vary. The environmental spectrum curves indicate the various types of environmental risks, and how much of each is present on the minimum risk routes. One can therefore infer the environmental vulnerability of the minimum risk routes at a glance from the environmental spectrum curves.

In conclusion, an investigation of the risks involved in the transportation of various classes of HM in a large urban area is a significant accomplishment in this study. Route designation for HM transportation between a given origin -

destination pair should be based on their individual classes rather than a single route for all types of HM.

8.2 RECOMMENDATION FOR FURTHER 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 :

1) Development of a detailed Geographical Information System for Quebec and other Provinces in Canada. This will facilitate in determining safe routes for transporting HM in any part of Canada.

2) Further studies have to be done to establish the truck volume and, truck accident rates for different types of roadway in Quebec and in Canada.

3) Another major problem was in quantifying risk. Given an accident involving a truck carrying a HM, there are several types of risks in terms of fatalities, injuries, damage to buildings, plants and animals, soil, etc. Further studies have to be done on a method of quantifying these risk to a single unit, in order to facilitate the routing process.

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APPENDIX - A

TABLES

This appendix contains tables for the database, tables for risk to population and environmental risk for the study region, and also tables for risk optimization where the risks are normalized and criteria weights applied and varied to obtain minimum risk. These tables cover several pages but, due to lack of space, only four pages of each table is presented in this appendix.

The tables listed here include:

1. A.1 Database.
2. A.2 Risk to population and risk to environment for study region.
3. A.3 Risk Minimization.

Table A.1 Database

Node from	Node to	Dist (km)	Pop ($/km^2$)	ENVIRONMENTAL COMPONENTS (km^2) Farm land	Fauna	Lake	River	Tour. &Rec.	Forest	Mining	Soil
1	2	23	13	23	0	0	0	0	0	0	23
1	41	72	11	0	0	0	0	0	0	0	72
2	1	23	13	23	0	0	0	0	0	0	23
2	3	21	85	0	0	0	0	0	0	0	21
2	40	83	31	0	0	0	0	0	0	0	83
3	2	21	85	0	0	0	0	0	0	0	21
3	4	31	179	0	0	0	0	0	0	0	31
3	7	34	62	0	0	0	0	0	0	0	34
3	17	32	47	0	0	0	0	0	0	0	32
4	3	31	179	0	0	0	0	0	0	0	31
4	5	3	206	0	0	0	0	0	0	0	3
4	7	13	536	0	0	0	0	0	0	0	13
5	4	3	206	0	0	0	0	0	0	0	3
5	6	11	717	0	0	0	0	0	0	0	11
5	15	1	206	0	0	0	0	0	0	0	1
5	16	2	206	0	0	0	0	0	0	0	2
6	5	11	717	0	0	0	0	0	0	0	11
6	7	2	717	0	0	0	0	0	0	0	2
7	3	34	62	0	0	0	0	0	0	0	34
7	4	13	536	0	0	0	0	0	0	0	13
7	6	2	717	0	0	0	0	0	0	0	2
8	9	8	970	0	0	0	0	0	0	0	8
8	10	6	1889	0	0	0	0	0	0	0	6
9	8	8	970	0	0	0	0	0	0	0	8
9	10	9	970	0	0	0	0	0	0	0	9
10	8	6	1889	0	0	0	0	0	0	0	6
10	9	9	970	0	0	0	0	0	0	0	9
10	11	4	1889	0	0	0	0	0	0	0	4

Table A.1 ...(Continued)

Node from	Node to	Dist (km)	Pop ($/km^2$)	ENVIRONMENTAL COMPONENTS (km^2)							
				Farm land	Fauna	Lake	River	Tour. &Rec.	Forest	Mining	Soil
11	10	4	1889	0	0	0	0	0	0	0	4
11	12	4	1889	0	0	0	0	0	0	0	4
11	13	8	1889	0	0	0	0	0	0	0	8
12	11	4	1889	0	0	0	0	0	0	0	4
12	13	3	849	0	0	0	0	0	0	0	3
12	14	5	849	0	0	0	0	0	0	0	5
13	11	8	1889	0	0	0	0	0	0	0	8
13	12	3	849	0	0	0	0	0	0	0	3
13	14	4	849	0	0	0	0	0	0	0	4
13	20	7	616	0	0	0	0	0	0	0	7
14	12	5	849	0	0	0	0	0	0	0	5
14	13	4	849	0	0	0	0	0	0	0	4
14	15	4	849	0	0	0	0	0	0	0	4
15	5	1	206	1	0	0	0	0	0	0	1
15	14	4	849	0	0	0	0	0	0	0	4
15	16	2	206	0	0	0	0	0	0	0	2
15	19	9	206	0	0	0	0	0	0	0	9
16	5	2	206	0	0	0	0	0	0	0	2
16	15	2	206	0	0	0	0	0	0	0	2
16	17	12	77	0	0	0	0	0	0	0	12
16	18	8	206	0	0	0	0	0	0	0	8
17	3	32	47	0	0	0	0	0	0	0	32
17	16	12	77	0	0	0	0	0	0	0	12
17	18	4	68	0	0	0	0	0	0	0	4
17	38	88	25	0	0	0	0	0	0	0	88
18	16	8	206	0	0	0	0	0	0	0	8
18	17	4	68	0	0	0	0	0	0	0	4
18	19	4	163	0	0	0	0	0	0	0	4
18	33	70	34	0	0	0	0	0	0	0	70

Table A.1 ...(Continued)

Node from	Node to	Dist (km)	Pop. (/km^2)	ENVIRONMENTAL COMPONENTS (km^2)							
				Farm land	Fauna	Lake	River	Tour. &Rec.	Forest	Mining	Soil
19	15	9	206	0	0	0	0	0	0	0	9
19	18	4	163	0	0	0	0	0	0	0	4
19	30	104	25	104	104	0	104	0	0	0	104
20	13	7	616	0	0	0	0	0	0	0	7
20	21	52	98	0	52	0	52	0	0	0	52
20	22	54	91	0	0	0	0	0	0	0	54
21	20	52	98	0	52	0	52	0	0	0	52
21	22	2	21	0	0	0	0	0	0	0	2
21	25	38	62	38	0	0	38	0	0	0	38
22	20	54	91	0	0	0	0	0	0	0	54
22	21	2	21	0	0	0	0	0	0	0	2
22	25	37	62	0	0	0	0	0	0	0	37
23	24	12	350	0	0	0	0	0	0	0	12
23	25	32	383	0	0	0	0	0	0	0	32
24	23	12	350	0	0	0	0	0	0	0	12
24	27	25	343	0	0	0	0	0	0	0	25
24	69	29	27	29	0	0	0	0	0	0	29
25	21	38	62	38	0	0	38	0	0	0	38
25	22	37	62	0	0	0	0	0	0	0	37
25	23	32	383	0	0	0	0	0	0	0	32
25	26	9	300	0	0	0	0	0	0	0	9
26	25	9	300	0	0	0	0	0	0	0	9
26	27	4	699	0	0	0	0	0	0	0	4
26	28	2	699	0	0	0	0	0	0	0	2
27	24	25	343	0	0	0	0	0	0	0	25
27	26	4	699	0	0	0	0	0	0	0	4
27	75	10	305	0	0	0	0	0	0	0	10
28	26	2	699	0	0	0	0	0	0	0	2
28	29	3	26	0	0	0	0	0	0	0	3

Table A.1 ...(Continued)

Node from	Node to	Dist (km)	Pop. (/km²)	ENVIRONMENTAL COMPONENTS (km²)							
				Farm land	Fauna	Lake	River	Tour. &Rec.	Forest	Mining	Soil
28	75	13	269	0	0	0	0	0	0	0	13
29	28	3	26	0	0	0	0	0	0	0	3
29	30	13	26	0	13	0	0	0	0	0	13
29	31	1	26	0	0	0	0	0	0	0	1
29	66	43	21	43	43	0	0	0	0	0	43
30	19	104	25	104	104	0	104	0	0	0	104
30	29	13	26	0	13	0	0	0	0	0	13
30	31	10	26	0	0	0	0	0	0	0	10
31	29	1	26	1	0	0	0	0	0	0	1
31	30	10	26	0	0	0	0	0	0	0	10
31	32	12	26	12	0	0	0	0	0	0	12
32	31	12	26	12	0	0	0	0	0	0	12
32	34	20	11	0	0	0	0	0	0	0	20
32	35	22	14	22	0	0	0	0	0	0	22
33	18	70	34	0	0	0	0	0	0	0	70
33	34	25	14	0	0	0	0	0	0	0	25
33	37	24	48	0	0	0	0	0	0	0	24
34	32	20	11	0	0	0	0	0	0	0	20
34	33	25	14	0	0	0	0	0	0	0	25
34	35	10	12	0	0	0	0	0	0	0	10
34	36	20	13	0	0	0	0	0	0	0	20
35	32	22	14	22	0	0	0	0	0	0	22
35	34	10	12	0	0	0	0	0	0	0	10
35	65	23	22	0	0	0	0	0	0	0	23
36	34	20	13	0	0	0	0	0	0	0	20
36	37	3	126	0	0	0	0	0	0	0	3
36	64	48	22	0	0	0	0	0	0	0	48
37	33	24	48	0	0	0	0	0	0	0	24

TABLE A.2 RISK TO POPULATION AND RISK TO ENVIRONMENT FOR STUDY REGION

Node From	Node To	Dist. (km)	Pop. (pers/km²)	Traff. Vol. AADT	RAR per 10^6km	Vol. Trucks	Acc. Rate	LPG Risk Pop Fatal.	LPG Risk Env 10^6m³	Chlorine Fatal.	Sulph. Acid Env. (km³)
1	2	23	13	6480	0.118	1026	1.12	0.02184	0.112	0.127	0.0560
1	41	72	11	2495	0.124	300	0.98	0.01617	0.049	0.094	0.0490
2	1	23	13	6480	0.118	1026	1.12	0.02184	0.112	0.127	0.0560
2	3	21	85	9295	0.118	1394	1.26	0.16065	0.063	0.348	0.0645
2	40	83	31	5920	0.124	711	1.29	0.06000	0.065	0.720	0.1335
3	2	21	85	9295	0.118	1394	1.26	0.16065	0.063	0.348	0.0645
3	4	31	179	11320	0.039	2264	1.00	0.26850	0.050	1.557	0.0500
3	7	34	62	3754	0.124	451	0.69	0.06417	0.035	0.372	0.0345
3	17	32	47	2024	0.124	243	0.35	0.02468	0.018	0.057	0.0065
4	3	31	179	11320	0.039	2264	1.00	0.26850	0.050	1.557	0.0500
4	5	3	206	2260	0.124	271	0.04	0.01236	0.002	0.072	0.0020
4	7	13	536	23010	0.039	4602	0.85	0.68340	0.043	4.663	0.0500
5	4	3	206	2260	0.124	271	0.04	0.01236	0.002	0.072	0.0020
5	6	11	717	2260	0.124	271	0.13	0.13982	0.007	0.811	0.0500
5	15	1	206	2260	0.124	271	0.01	0.00309	0.001	0.090	0.0020
5	16	2	206	2260	0.124	271	0.02	0.00618	0.001	0.036	0.0065
6	5	11	717	2260	0.124	271	0.13	0.13982	0.007	0.811	0.0025
6	7	2	717	2260	0.124	271	0.02	0.02151	0.001	0.125	0.0010
7	3	34	62	3754	0.124	451	0.69	0.06417	0.035	0.372	0.0065
7	4	13	536	23010	0.039	2264	1.00	0.8040	0.050	4.663	0.0010
7	6	2	717	2260	0.124	271	0.02	0.02151	0.001	0.125	0.0345
8	9	8	970	17070	0.118	2561	0.88	1.2804	0.044	7.426	0.0500
8	10	6	1889	10610	0.118	1592	0.41	1.1617	0.021	6.738	0.0010
9	8	8	970	17070	0.118	2561	0.88	1.2804	0.044	7.426	0.0440
9	10	9	970	10610	0.118	1592	0.62	0.9021	0.031	5.232	0.0205
10	8	6	1889	10610	0.118	1592	0.41	1.1617	0.021	6.738	0.0440
10	9	9	970	10610	0.118	1592	0.62	0.9021	0.031	5.232	0.0310

Table A.2 ...(Continued)

Node From	Node To	Dist. (km)	Pop. (pers/km²)	Traff. Vol. AADT	RAR per 10^6km	Vol. Trucks	Acc. Rate	LPG Risk		Chlorine Fatal.	Sulph. Acid Env. (km³)
								Pop Fatal.	Env 10^6m³		
10	11	4	1889	10610	0.118	1592	0.27	0.7650	0.014	4.437	0.0205
11	10	4	1889	10610	0.118	1592	0.27	0.7650	0.027	4.437	0.0310
11	12	4	1889	10610	0.118	1592	0.27	0.7650	0.014	4.437	0.0135
11	13	8	1889	6670	0.118	1001	0.34	0.9634	0.017	5.588	0.0170
12	11	4	1889	10610	0.118	1592	0.27	0.7650	0.014	4.437	0.0135
12	13	3	849	6670	0.118	1001	0.13	0.16556	0.007	0.960	0.0065
12	14	5	849	6670	0.118	1001	0.22	0.2802	0.011	0.960	0.0065
13	11	8	1889	6670	0.118	1001	0.34	0.96339	0.030	5.588	0.0170
13	12	3	849	6670	0.118	1001	0.13	0.16556	0.007	0.960	0.0065
13	14	4	849	6670	0.118	1001	0.17	0.21650	0.009	0.960	0.0065
13	20	7	616	16880	0.039	3376	0.24	0.22176	0.041	1.822	0.0170
14	12	5	849	6670	0.118	1001	0.13	0.16556	0.007	0.960	0.0065
14	13	4	849	6670	0.118	1001	0.13	0.16556	0.007	0.960	0.0065
14	15	4	849	6670	0.118	1001	0.04	0.05094	0.002	0.591	0.0040
15	5	1	206	2260	0.124	272	0.05	0.01545	0.005	0.090	0.0025
15	14	4	849	6670	0.118	1001	0.08	0.10188	0.004	0.591	0.0040
15	16	2	206	6670	0.118	1001	0.39	0.12051	0.020	0.932	0.0260
15	19	9	206	2880	0.124	346	0.03	0.00927	0.002	1.129	0.0315
16	5	2	206	2660	0.124	272	0.02	0.00618	0.001	0.036	0.0010
16	15	2	206	6670	0.118	1001	0.52	0.16068	0.026	0.932	0.0260
16	17	12	77	2840	0.124	341	0.12	0.01386	0.006	0.027	0.0020
16	18	8	206	29060	0.039	5812	2.65	0.81885	0.133	0.591	0.0165
17	3	32	47	2024	0.124	343	0.13	0.00917	0.007	0.053	0.0065
17	16	12	77	2840	0.124	241	0.04	0.00462	0.002	0.027	0.0020
17	18	4	68	2700	0.124	324	1.29	0.13158	0.065	0.024	0.0020
17	38	88	25	3750	0.124	450	0.16	0.00600	0.008	0.389	0.0895
18	16	8	206	29060	0.039	5812	0.33	0.10197	0.017	0.591	0.0465
18	17	4	68	2700	0.124	241	0.04	0.00408	0.002	0.024	0.0020
18	19	4	163	2880	0.124	346	1.10	0.26895	0.055	0.389	0.0815

Table A.2 ...(Continued)

Node From	Node To	Dist. (km)	Pop. (pers/km²)	Traff. Vol. AADT	RAR per 10^6km	Vol. Trucks	Acc. Rate	LPG Risk		Chlo-rine Fatal.	Sulph. Acid Env. (km³)
								Pop Fatal.	Env 10^6m³		
18	33	70	34	24100	0.039	4820	0.62	0.03162	0.031	0.591	0.2400
19	15	9	206	2880	0.124	346	0.63	0.02457	0.032	0.024	0.0315
19	18	4	163	2880	0.124	346	1.63	0.39854	0.082	2.312	0.0815
19	30	104	25	3021	0.124	363	0.12	0.0045	0.024	1.420	0.0855
20	13	7	616	16880	0.039	3376	0.34	0.31084	0.030	1.822	0.0170
20	21	52	98	3197	0.118	480	1.12	0.16464	0.084	0.034	0.0020
20	22	54	91	13418	0.039	2684	1.99	0.27200	0.100	1.631	0.1030
12	20	52	98	3190	0.118	479	0.04	0.00588	0.015	0.034	0.0020
12	22	2	21	1940	0.124	233	0.40	0.00126	0.020	0.004	0.0010
12	25	38	62	1526	0.124	183	0.44	0.04092	0.066	0.167	0.0155
22	20	54	91	13418	0.039	2684	2.06	0.2816	0.103	1.631	0.1030
22	21	2	21	1940	0.124	233	0.02	0.00063	0.001	0.004	0.0010
22	25	37	62	11180	0.039	2236	1.18	0.10974	0.059	0.636	0.0590
23	24	12	350	820	0.235	82	0.08	0.0420	0.004	0.244	0.0040
23	25	32	383	8915	0.118	1338	1.84	1.0571	0.092	6.131	0.0920
24	23	12	350	820	0.235	82	0.08	0.0420	0.004	0.244	0.0040
24	27	25	343	14100	0.039	2820	1.00	0.5142	0.050	2.984	0.0500
24	69	29	27	1402	0.124	169	0.22	0.0089	0.022	0.052	0.0110
25	21	38	62	1526	0.124	183	0.31	0.0288	0.047	0.167	0.0155
25	22	37	62	11180	0.039	2236	1.18	0.1097	0.059	0.636	0.0590
25	23	32	383	8915	0.118	1338	1.84	1.0571	0.092	6.131	0.0920
25	26	9	300	13180	0.039	2636	0.34	0.1530	0.017	0.887	0.0170
26	25	9	300	13180	0.039	2636	0.34	0.1530	0.017	0.887	0.0170
26	27	4	699	14100	0.039	2820	0.16	0.1678	0.008	0.973	0.0080
26	28	2	699	14100	0.039	2820	0.08	0.0839	0.004	0.487	0.0040
27	24	25	343	14100	0.039	2820	1.00	0.5142	0.050	2.984	0.0500
27	26	4	699	14100	0.039	2820	0.16	0.1678	0.008	0.973	0.0080
27	75	10	305	18580	0.039	3716	0.53	0.2425	0.027	1.406	0.0265

Table A.2 ...(Continued)

Node From	Node To	Dist. (km)	Pop. (pers/km²)	Traff. Vol. AADT	RAR per 10^6km	Vol. Trucks	Acc. Rate	LPG Risk		Chlo-rine Fatal.	Sulph. Acid Env. (km³)
								Pop Fatal.	Env 10^6m^3		
28	26	2	699	14100	0.039	2820	0.08	0.0839	0.004	0.487	0.0040
28	29	3	26	14100	0.039	2820	0.12	0.0047	0.006	0.027	0.0060
28	75	13	269	2200	0.235	220	0.25	0.1009	0.013	0.585	0.0125
29	28	3	26	14100	0.039	2820	0.12	0.0047	0.006	0.027	0.0060
29	30	13	[illegible]	3620	0.235	362	0.38	0.0148	0.038	0.086	0.0190
29	31	1	26	14100	0.039	2820	0.04	0.0016	0.002	0.009	0.0020
29	66	43	21	3217	0.124	386	0.75	0.0236	0.113	0.137	0.0375
30	19	104	25	3021	0.124	363	1.71	0.06413	0.114	0.372	0.0855
30	29	13	26	2620	0.235	362	0.38	0.01482	0.038	0.086	0.0190
30	31	10	26	4600	0.039	920	0.13	0.0051	0.007	0.029	0.0065
31	29	1	26	14100	0.039	2820	0.04	0.0016	0.004	0.009	0.0020
31	30	10	26	4600	0.039	920	0.13	0.0051	0.007	0.029	0.0065
31	32	12	26	14100	0.39	2820	0.48	0.0187	0.048	0.109	0.0240
32	31	12	26	14100	0.039	2820	0.48	0.0187	0.048	0.109	0.0240
32	34	20	11	4685	0.118	703	0.61	0.0101	0.031	0.058	0.0305
32	35	22	14	4880	0.118	732	0.69	0.0145	0.069	0.084	0.0345
33	18	70	34	24100	0.039	4820	4.80	0.2448	0.120	1.420	0.2400
33	34	25	14	24100	0.039	4820	1.72	0.0361	0.086	0.209	0.0860
33	37	24	48	2514	0.124	302	0.33	0.0238	0.017	0.138	0.0165
34	32	20	11	4685	0.118	703	0.61	0.0101	0.031	0.058	0.0305
34	33	25	14	24100	0.039	4820	1.72	0.0361	0.086	0.209	0.0860
34	35	10	12	18810	0.039	3762	0.54	0.0097	0.027	0.056	0.0270
34	36	20	13	2785	0.124	334	0.30	0.0059	0.015	0.034	0.0150
35	32	22	14	4880	0.118	732	0.69	0.0145	0.069	0.084	0.0345
35	34	10	12	18810	0.039	3762	0.54	0.0097	0.027	0.056	0.0270
35	65	23	22	27133	0.039	5427	1.78	0.0587	0.089	0.341	0.0890
36	34	20	13	2785	0.124	334	0.30	0.0059	0.015	0.034	0.0150
36	37	3	126	7390	0.118	1109	0.14	0.0265	0.007	0.175	0.0080
36	64	48	22	4660	0.118	699	1.45	0.0479	0.073	0.278	0.0725

Table A.3 contains the normalized risk values for the various routes with the following criteria weightings :

Route R4	-	100% population risk,	0% environmental risk
Route R5	-	75% population risk,	25% environmental risk
Route R6	-	50% population risk,	50% environmental risk
Route R7	-	25% population risk,	75% environmental risk
Route R8	-	0% population risk,	100% environmental risk

Table A.3 ...(Continued)

Node From	Node To	Dist. (km)	Pop. (pers/km²)	Risk People (Fatalities)	Risk Env. $x10^6m^3$	Risk Pop. Norm. Route R4	Route R5	Route R6	Route R7	Risk Env. Norm. Route R8	Route R_{min}
1	2	23	13	0.02184	0.112	0.017	0.223	0.430	0.636	0.842	0.503
1	41	72	11	0.01617	0.049	0.013	0.102	0.191	0.279	0.368	0.222
2	1	23	13	0.02184	0.112	0.017	0.223	0.430	0.636	0.842	0.252
2	3	21	85	0.16065	0.063	0.047	0.154	0.261	0.367	0.474	0.299
2	40	83	31	0.06000	0.065	0.047	0.157	0.268	0.385	0.489	0.308
3	2	21	85	0.16065	0.063	0.125	0.213	0.300	0.387	0.474	0.331
3	4	31	179	0.2685	0.050	0.210	0.251	0.293	0.334	0.376	0.308
3	7	34	62	0.06417	0.035	0.050	0.103	0.157	0.210	0.263	0.176
3	17	32	47	0.02468	0.018	0.007	0.039	0.071	0.103	0.135	0.083
4	3	31	179	0.2685	0.050	0.210	0.251	0.293	0.334	0.376	0.308
4	5	3	206	0.01236	0.002	0.010	0.011	0.012	0.014	0.015	0.013
4	7	13	536	0.6834	0.043	0.534	0.481	0.429	0.376	0.323	0.410
5	4	3	206	0.01236	0.002	0.010	0.011	0.012	0.014	0.015	0.013
5	6	11	717	0.13982	0.007	0.109	0.095	0.081	0.067	0.053	0.076
5	15	1	206	0.00309	0.001	0.012	0.010	0.008	0.006	0.004	0.007
5	16	2	206	0.00618	0.001	0.005	0.005	0.006	0.007	0.008	0.006
6	5	11	717	0.13982	0.007	0.109	0.095	0.081	0.067	0.053	0.075
6	7	2	717	0.02151	0.001	0.017	0.014	0.012	0.010	0.008	0.011
7	3	34	62	0.06417	0.035	0.050	0.103	0.157	0.210	0.263	0.176
7	4	13	536	0.8040	0.050	0.628	0.565	0.502	0.439	0.376	0.479
7	6	2	717	0.02151	0.001	0.017	0.014	0.012	0.010	0.008	0.011
8	9	8	970	1.2804	0.044	1.000	0.833	0.665	0.498	0.331	0.605
8	10	6	1889	1.1617	0.021	0.907	0.720	0.533	0.345	0.158	0.465
9	8	8	970	1.2804	0.044	1.000	0.833	0.665	0.498	0.331	0.605
9	10	9	970	0.9021	0.031	0.705	0.587	0.469	0.351	0.233	0.426
10	8	6	1889	1.1617	0.021	0.907	0.720	0.533	0.345	0.158	0.465
10	9	9	970	0.9021	0.031	0.705	0.587	0.469	0.351	0.233	0.426
10	11	4	1889	0.7650	0.014	0.597	0.474	0.351	0.228	0.105	0.307

Table A.3 ...(Continued)

Node From	Node To	Dist. (km)	Pop. (pers/ km^2)	Risk People (Fatalities)	Risk Env. $x10^6m^3$	Risk Pop. Norm. Route R4	Route R5	Route R6	Route R7	Risk Env. Norm Route R8	Route R_{min}
11	10	4	1889	0.7650	0.027	0.597	0.499	0.401	0.303	0.205	0.366
11	12	4	1889	0.7650	0.014	0.597	0.474	0.351	0.228	0.105	0.307
11	13	8	1889	0.9634	0.017	0.752	0.596	0.440	0.284	0.128	0.384
12	11	4	1889	0.7650	0.014	0.597	0.474	0.351	0.228	0.105	0.307
12	13	3	849	0.16556	0.007	0.129	0.110	0.091	0.072	0.053	0.084
12	14	5	849	0.2802	0.011	0.219	0.185	0.151	0.117	0.083	0.139
13	11	8	1889	0.96339	0.030	0.752	0.621	0.490	0.359	0.228	0.443
13	12	3	849	0.16556	0.007	0.129	0.110	0.091	0.072	0.053	0.084
13	14	4	849	0.21650	0.009	0.169	0.144	0.118	0.093	0.068	0.109
13	20	7	616	0.22176	0.041	0.173	0.207	0.241	0.275	0.308	0.253
14	12	5	849	0.16556	0.007	0.129	0.110	0.091	0.072	0.053	0.084
14	13	4	849	0.16556	0.007	0.129	0.110	0.091	0.072	0.053	0.084
14	15	4	849	0.05094	0.002	0.040	0.034	0.027	0.021	0.015	0.025
15	5	1	206	0.01545	0.005	0.012	0.140	0.160	0.180	0.019	0.017
15	14	4	849	0.10188	0.004	0.080	0.067	0.055	0.042	0.030	0.050
15	16	2	206	0.12051	0.020	0.169	0.108	0.122	0.136	0.150	0.127
15	19	9	206	0.00927	0.002	0.007	0.009	0.011	0.013	0.015	0.012
16	5	2	206	0.00618	0.001	0.004	0.005	0.006	0.007	0.008	0.006
16	15	2	206	0.16068	0.026	0.125	0.143	0.160	0.178	0.195	0.167
16	17	12	77	0.01386	0.006	0.011	0.019	0.028	0.037	0.045	0.031
16	18	8	206	0.81885	0.133	0.640	0.730	0.820	0.910	1.000	0.852
17	3	32	47	0.00917	0.007	0.007	0.019	0.030	0.041	0.053	0.034
17	16	12	77	0.00462	0.002	0.004	0.006	0.009	0.012	0.015	0.010
17	18	4	68	0.13158	0.065	0.103	0.199	0.296	0.392	0.489	0.330
17	38	88	25	0.0060	0.008	0.005	0.019	0.032	0.046	0.060	0.037
18	16	8	206	0.10197	0.017	0.080	0.092	0.104	0.116	0.128	0.108
18	17	4	68	0.00408	0.002	0.003	0.006	0.009	0.012	0.015	0.010
18	19	4	163	0.26895	0.055	0.210	0.261	0.312	0.363	0.414	0.330
18	33	70	34	0.03162	0.031	0.025	0.077	0.129	0.181	0.233	0.148

Table A.3 ...(Continued)

Node From	Node To	Dist. (km)	Pop. (pers/km²)	Risk People (Fatalities)	Risk Env. x10⁶m³	Risk Pop. Norm. Route R4	Route R5	Route R6	Route R7	Risk Env. Norm. Route R8	Route R_{min}
19	15	9	206	0.02457	0.032	0.019	0.075	0.130	0.185	0.241	0.150
19	18	4	163	0.39854	0.082	0.311	0.388	0.464	0.540	0.617	0.491
19	30	104	25	0.0045	0.024	0.004	0.048	0.092	0.136	0.180	0.108
20	13	7	616	0.31084	0.030	0.243	0.239	0.236	0.232	0.228	0.234
20	21	52	98	0.16464	0.084	0.129	0.254	0.380	0.506	0.632	0.425
20	22	54	91	0.272	0.100	0.212	0.347	0.482	0.617	0.752	0.531
21	20	52	98	0.00588	0.015	0.005	0.033	0.060	0.088	0.115	0.070
21	22	2	21	0.00126	0.020	0.001	0.038	0.076	0.113	0.150	0.089
21	25	38	62	0.04092	0.066	0.032	0.148	0.264	0.380	0.017	0.245
22	20	54	91	0.2816	0.103	0.220	0.359	0.497	0.636	0.774	0.547
22	21	2	21	0.00063	0.001	0.001	0.002	0.004	0.006	0.008	0.005
22	25	37	62	0.10974	0.059	0.086	0.175	0.265	0.354	0.444	0.297
23	24	12	350	0.042	0.004	0.033	0.032	0.031	0.031	0.030	0.031
23	25	32	383	1.0571	0.092	0.826	0.792	0.759	0.725	0.692	0.747
24	23	12	350	0.042	0.004	0.033	0.032	0.031	0.031	0.030	0.031
24	27	25	343	0.5142	0.050	0.402	0.395	0.389	0.382	0.376	0.386
24	69	29	27	0.00891	0.022	0.007	0.047	0.086	0.126	0.165	0.100
25	21	38	62	0.02883	0.047	0.023	0.047	0.070	0.094	0.117	0.073
25	22	37	62	0.10974	0.059	0.141	0.175	0.265	0.354	0.444	0.297
25	23	32	383	1.0571	0.092	0.826	0.792	0.759	0.725	0.692	0.747
25	26	9	300	0.1530	0.017	0.119	0.122	0.124	0.126	0.128	0.124
26	25	9	300	0.1530	0.017	0.119	0.122	0.124	0.126	0.128	0.124
26	27	4	699	0.16776	0.008	0.131	0.113	0.096	0.078	0.060	0.089
26	28	2	699	0.08388	0.004	0.066	0.057	0.048	0.039	0.030	0.045
27	24	25	343	0.5142	0.050	0.402	0.395	0.389	0.382	0.376	0.386
27	26	4	699	0.16776	0.008	0.131	0.113	0.096	0.078	0.060	0.089
27	75	10	305	0.2425	0.027	0.189	0.193	0.196	0.200	0.203	0.197
28	26	2	699	0.08388	0.004	0.066	0.072	0.078	0.083	0.089	0.080
28	29	3	26	0.00468	0.006	0.004	0.014	0.024	0.035	0.045	0.028

Table A.3 ...(Continued)

Node From	Node To	Dist. (km)	Pop. (pers/ km^2)	Risk People (Fatalities)	Risk Env. $x10^6m^3$	Risk Pop. Norm. Route R4	Route R5	Route R6	Route R7	Risk Env. Norm. Route R8	Route R_{min}
28	75	13	269	0.10088	0.013	0.079	0.083	0.089	0.093	0.098	0.090
29	28	3	26	0.00468	0.006	0.004	0.014	0.024	0.035	0.045	0.028
29	30	13	26	0.01482	0.038	0.012	0.080	0.148	0.217	0.286	0.173
29	31	1	26	0.00156	0.002	0.001	0.005	0.008	0.012	0.015	0.009
29	66	43	21	0.02363	0.113	0.018	0.226	0.434	0.642	0.281	0.509
30	19	104	25	0.06413	0.114	0.050	0.198	0.347	0.495	0.432	0.391
30	29	13	26	0.01482	0.038	0.012	0.045	0.078	0.111	0.123	0.087
30	31	10	26	0.00507	0.007	0.004	0.016	0.028	0.040	0.053	0.033
31	29	1	26	0.00156	0.004	0.001	0.010	0.020	0.020	0.020	0.020
31	30	10	26	0.00507	0.007	0.004	0.016	0.028	0.040	0.053	0.033
31	32	12	26	0.01872	0.048	0.015	0.101	0.188	0.274	0.145	0.017
32	31	12	26	0.01872	0.048	0.015	0.016	0.017	0.018	0.018	0.017
32	34	20	11	0.0101	0.031	0.008	0.064	0.120	0.177	0.233	0.141
32	35	22	14	0.01449	0.069	0.011	0.138	0.265	0.392	0.519	0.311
33	18	70	34	0.2448	0.120	0.191	0.369	0.547	0.724	0.902	0.611
33	34	25	14	0.03612	0.086	0.028	0.183	0.337	0.492	0.647	0.393
33	37	24	48	0.02376	0.017	0.019	0.046	0.073	0.101	0.1280	0.083
34	32	20	11	0.01007	0.031	0.008	0.064	0.120	0.177	0.230	0.141
34	33	25	14	0.03612	0.086	0.028	0.183	0.337	0.492	0.647	0.393
34	35	10	12	0.00972	0.027	0.008	0.056	0.105	0.154	0.203	0.123
34	36	20	13	0.00585	0.015	0.005	0.032	0.059	0.086	0.113	0.068
35	32	22	14	0.01449	0.069	0.011	0.015	0.019	0.022	0.026	0.020
35	34	10	12	0.00972	0.027	0.008	0.056	0.105	0.154	0.203	0.123
35	65	23	22	0.05874	0.089	0.046	0.202	0.358	0.513	0.669	0.414
36	34	20	13	0.00585	0.015	0.005	0.032	0.059	0.086	0.113	0.068
36	37	3	126	0.02646	0.007	0.021	0.029	0.037	0.045	0.053	0.040
36	64	48	22	0.04785	0.073	0.037	0.165	0.293	0.421	0.549	0.339
37	33	24	48	0.02376	0.017	0.019	0.046	0.073	0.101	0.128	0.083

APPENDIX - B

TABLES AND RISK OPTIMIZATION

This appendix is made up of two sections - section A and section B. Section A is made up of tables and detailed results for the O-D pairs in the study region. Minimum exposure units criteria are used to obtain these routes. Section B contains the risk optimization and risk dissipation curves of the O-D pairs.

Results were developed for all the O-D pairs. Due to lack of space, results for four O-D pairs - Montreal - Quebec City, Montreal - Sherbrooke, Trois-Rivieres - Quebec City, Drummondville - Quebec City are presented in this appendix.

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SECTION A

O-D PAIR: MONTREAL - QUEBEC CITY

Table B.1: ROUTE R1

NODE NO.	NODE FROM	NODE TO	DISTANCE (km)	PPOP. DEN. (pers/km²)	POP. (persons)	ENV. COMP (km²)
1	23	25	37	62	2294	0
2	25	21	38	62	2356	0
3	21	20	52	98	5096	0
4	20	22	54	91	4914	0
5	22	28	2	699	1398	0
6	28	29	21	30	630	0
7	29	67	7	31	217	0
8	67	69	32	34	1088	32
9	69	24	29	27	783	29
10	24	26	12	350	4200	0
11	26	27	32	383	12256	0
12	27	18	37	62	2294	0
13	18	16	6	206	1236	0
14	16	13	7	616	4312	0
15	13	11	8	1889	15112	0
16	11	10	4	1889	7556	0
17	10	8	6	1889	1334	0
TOTAL	-	-	384	-	77076	61

Table B.2: ROUTE R2

NODE NO	NODE FROM	NODE TO	DISTANCE (km)	POP.DEN. (pers/km²)	POP. (persons)	ENV.COMP. (km²)
1	23	25	37	62	2294	0
2	25	21	38	62	2356	0
3	21	20	52	98	5096	0
4	20	22	54	91	4914	0
5	22	34	2	21	42	0
6	34	36	20	13	260	0
7	36	37	3	126	378	0
8	37	38	5	1332	6660	0
9	38	39	6	1332	7992	0
10	39	62	50	22	1100	0
11	62	63	6	18	108	6
12	63	66	23	19	437	23
13	66	71	3	197	591	0
14	71	65	4	1144	4576	0
15	65	35	23	22	506	0
16	35	34	10	12	120	0
17	34	33	25	14	350	0
18	33	18	70	34	2380	0
19	18	16	6	206	1236	0
20	16	15	3	206	618	0
21	15	14	4	849	3396	0
22	14	12	5	849	4245	0
23	12	11	4	1889	7556	0
24	11	10	4	1889	7556	0
25	10	8	6	1889	11334	0
TOTAL	-	-	463	-	76101	29

Table B.3: ROUTE R3

NODE NO	NODE FROM	NODE TO	DISTANCE (km)	POP DEN. (pers/km²)	POP. (persons)	ENV.COMP. (km²)
1	23	25	37	62	2294	0
2	25	21	38	62	2356	0
3	21	20	52	98	5096	0
4	20	22	54	91	4914	0
5	22	39	2	21	42	0
6	39	40	20	13	260	0
7	40	42	3	126	378	0
8	42	59	15	948	14220	0
9	59	57	22	36	792	0
10	57	56	31	37	1147	0
11	56	55	2	589	1178	0
12	55	64	43	20	860	0
13	64	65	23	21	483	0
14	65	66	9	130	1170	0
15	66	71	3	1144	3432	0
16	71	70	4	1144	4576	0
17	70	35	23	22	506	0
18	35	34	10	12	120	0
19	34	33	25	14	350	0
20	33	18	70	34	2380	0
21	18	16	6	206	1236	0
22	16	15	3	206	618	0
23	15	14	4	849	3396	0
24	14	12	5	849	4245	0
25	12	11	8	1889	15112	0
26	11	10	4	1889	7556	0
27	10	8	6	1889	11334	0
TOTAL	-	-	522	-	90051	0

O-D PAIR: MONTREAL - SHERBROOKE

Table B.4: ROUTE R1

NODE NO	NODE FROM	NODE TO	DISTANCE (km)	POP.DEN. (pers/km²)	POP. (persons)	ENV.COMP. (km²)
1	23	25	32	62	1984	0
2	25	21	38	62	2356	0
3	21	20	52	98	5096	0
4	20	13	7	616	4312	0
5	13	41	4	849	3396	0
6	41	46	26	300	7800	0
7	46	47	3	350	1050	0
8	47	49	27	29	783	0
9	49	50	5	610	3050	5
10	50	48	38	33	1254	38
11	48	57	47	36	1692	0
12	57	56	3	299	897	0
13	56	55	3	299	897	0
14	55	58	7	97	679	0
15	58	59	9	284	2556	0
16	59	45	5	1372	6860	0
TOTAL	-	-	306	-	44662	43

Table B.5: ROUTE R2

NODE NO	NODE FROM	NODE TO	DISTANCE (km)	POP. DEN. (pers/km²)	POP. (persons)	ENV.COMP. (km²)
1	23	25	32	62	1984	0
2	25	21	38	62	2356	0
3	21	20	52	98	5096	0
4	20	13	7	616	4312	0
5	13	24	5	849	4245	0
6	24	69	29	27	783	0
7	69	67	32	34	1088	0
8	67	68	29	18	522	29
9	68	75	7	75	525	0
10	75	28	13	269	3497	0
11	28	29	3	36	108	0
12	29	31	1	26	26	0
13	31	32	12	26	312	12
14	32	34	20	11	220	0
15	34	33	25	14	350	0
16	33	18	70	34	2380	0
17	18	17	4	68	272	0
18	17	3	32	47	1504	0
19	3	2	21	85	1785	0
20	2	1	23	13	299	23
21	1	41	72	11	792	0
22	41	42	26	6	78	0
23	42	43	54	10	540	0
24	43	45	6	74	444	0
TOTAL	-	-	613	-	33518	64

Table B.6: ROUTE R3

NODE NO	NODE FROM	NODE TO	DISTANCE (km)	POP. DEN. (pers/km²)	POP. (persons)	ENV.COMP. (km²)
1	23	25	32	62	1984	0
2	25	21	38	62	2356	0
3	21	20	52	98	5096	0
4	20	38	54	91	4914	0
5	38	39	3	13	39	0
6	39	40	6	126	756	0
7	40	42	7	488	3416	0
8	42	47	15	948	14220	0
9	47	51	22	36	792	0
10	51	56	31	37	1147	0
11	56	55	2	589	1178	0
12	55	57	48	36	1728	0
13	57	54	5	299	1495	0
14	54	65	3	920	2790	0
15	65	58	7	97	679	0
16	58	59	9	284	2556	0
17	59	45	5	1372	6860	0
TOTAL	-	-	339	-	52006	0

O-D PAIR: TROIS-RIVIERES - QUEBEC CITY

Table B.7: ROUTE R1

NODE NO	NODE FROM	NODE TO	DISTANCE (km)	POP. DEN. (pers/km²)	POP. (persons)	ENV.COMP. (km²)
1	26	25	9	300	2700	0
2	25	21	38	62	2356	38
3	21	20	52	98	5096	52
4	20	13	7	616	4312	0
5	13	12	3	849	2547	0
6	12	11	4	1889	7556	0
7	11	10	4	1889	7556	0
8	10	8	6	1889	11334	0
TOTAL	-	-	123	-	43457	92

Table B.8: ROUTE R2

NODE NO	NODE FROM	NODE TO	DISTANCE (km)	POP. DEN. (pers/km²)	POP. (persons)	ENV.COMP. (km²)
1	26	28	2	699	1398	0
2	28	29	3	26	78	0
3	29	31	1	26	26	0
4	31	30	10	26	260	0
5	30	19	104	25	2600	104
6	19	15	9	206	1854	0
7	15	14	4	849	3396	0
8	14	12	5	849	4245	0
9	12	11	4	1889	7556	0
10	11	10	4	1889	7556	
11	10	8	6	1889	11334	0
TOTAL	-	-	152	-	40303	104

Table B.9: ROUTE R3

NODE NO	NODE FROM	NODE TO	DISTANCE (km)	POP. DEN. (pers/km²)	POP. (persons)	ENV.COMP. (km²)
1	26	25	9	300	2700	0
2	25	22	37	62	2294	0
3	22	20	54	91	4914	0
4	20	13	7	616	4312	0
5	13	11	8	1889	15112	0
6	11	10	4	1889	7556	0
7	10	8	6	1889	11334	0
TOTAL	-	-	125	-	48222	0

O-D PAIR: DRUMMONDVILLE - QUEBEC CITY

Table B.10: ROUTE R1

NODE NO	NODE FROM	NODE TO	DISTANCE (km)	POP. DEN. (pers/km²)	POP. (persons)	ENV.COMP. (km²)
1	64	65	3	1144	3432	0
2	65	35	23	22	506	0
3	35	34	10	12	120	0
4	34	33	25	14	350	0
5	33	18	70	34	2380	0
6	18	16	6	206	1236	0
7	16	15	3	206	618	0
8	15	14	4	849	3396	0
9	14	12	5	849	4245	0
10	12	11	4	1889	7556	0
11	11	10	4	1889	7556	0
12	10	8	6	1889	11334	0
TOTAL	-	-	164	-	42729	0

Table B.11: ROUTE R2

NODE NO	NODE FROM	NODE TO	DISTANCE (km)	POP. DEN. (pers/km²)	POP. (persons)	ENV.COMP. (km²)
1	64	36	48	22	1056	0
2	36	34	20	13	260	0
3	34	33	25	14	350	0
4	33	18	70	34	2380	0
5	18	17	4	68	272	0
6	17	16	12	77	924	0
7	16	15	2	206	412	0
8	15	14	4	849	3396	0
9	14	12	5	849	4245	0
10	12	11	4	1889	7556	0
11	11	10	4	1889	7556	0
12	10	8	6	1889	11334	0
TOTAL	-	-	204	-	39741	0

Table B.12: ROUTE R3

NODE NO	NODE FROM	NODE TO	DISTANCE (km)	POP. DEN. (pers/km^2)	POP. (persons)	ENV.COMP. (km^2)
1	64	36	48	22	1056	0
2	36	34	20	13	260	0
3	34	33	25	14	350	0
4	33	18	70	34	2380	0
5	18	16	6	206	1236	0
6	16	15	3	206	824	0
7	15	14	4	846	3384	0
8	14	12	5	846	4230	0
9	12	11	4	1889	7556	0
10	11	10	4	1889	7556	0
11	10	8	6	1889	11334	0
TOTAL	-	-	195	-	40166	0

SECTION B

O-D PAIR: MONTREAL - QUEBEC CITY

Table B.13: RISK OPTIMIZATION

ROUTE	% RISK POPULATION	% RISK ENVIRONMENT	NORMALIZED RISK UNITS
R4	100	0	5.981
R5	75	25	5.729
R6	50	50	5.354
R_{min}	39	61	5.137
R7	25	75	5.196
R8	0	100	5.234

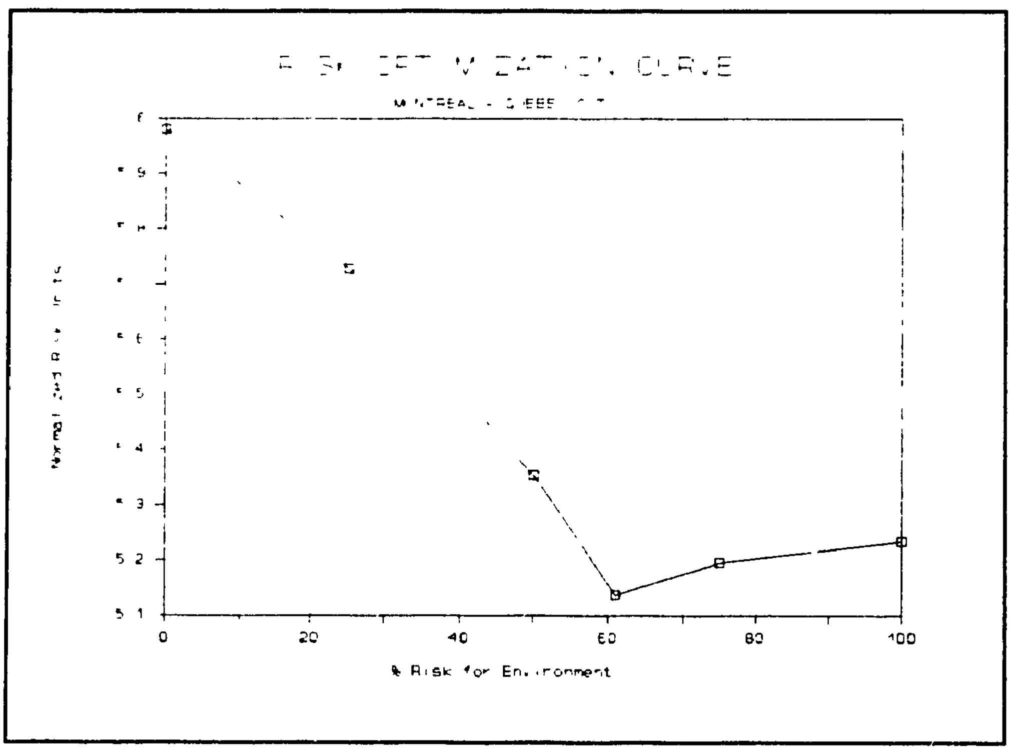

Figure B.1: Risk Optimization Curve

Table B.14: RISK DISSIPATION (LPG)

LINK NO	NODE NO	DISTANCE (km)	CUMM.DIS (km)	T.NORM. RISK UNITS	RISK POP. (NORM. UNITS)	RISK ENV. (NORM UNITS)
0	23	0	0	5.137	2.003	3.134
1	25	37	37	4.390	1.712	2.678
2	21	38	75	4.317	1.684	2.633
3	20	52	127	4.247	1.656	2.591
4	22	54	181	3.716	1.449	2.267
5	28	2	183	3.169	1.236	1.933
6	29	21	204	3.141	1.225	1.916
7	67	7	211	2.632	1.026	1.606
8	69	32	243	2.075	0.809	1.266
9	24	29	272	2.063	0.805	1.258
10	26	12	284	1.677	0.654	1.023
11	27	32	316	1.588	0.619	0.969
12	18	37	353	1.391	0.542	0.849
13	16	6	359	1.283	0.500	0.783
14	13	7	366	1.116	0.435	0.681
15	11	8	374	0.673	0.262	0.411
16	10	4	378	0.307	0.120	0.187
17	8	6	384	0	0	0

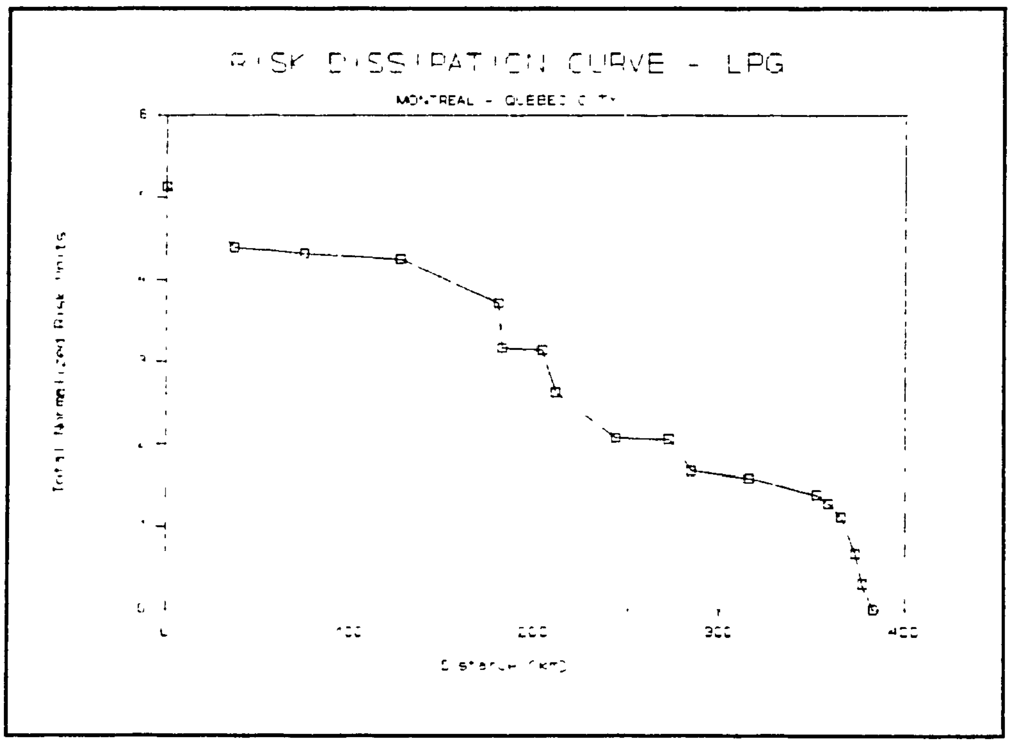

Figure B.2: TOTAL RISK DISSIPATION CURVE (LPG)

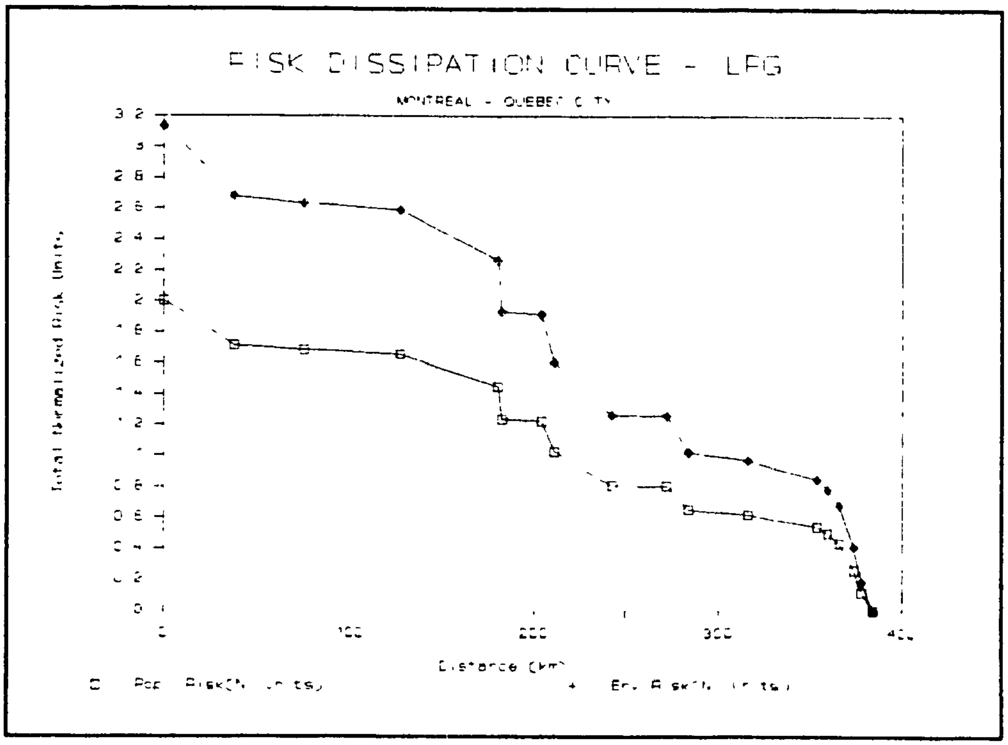

Figure B.3: INDIVIDUAL RISK DISSIPATION CURVES (LPG)

Table B.15: ENVIRONMENTAL RISK (LPG)

LINK NO	CUMM. DIST. (km)	CUMM. RISK (Soil, km^3)	CUMM. RISK (Farms, km^2)
0	0	0	0
1	37	0.092	0
2	75	0.139	0
3	127	0.154	0
4	181	0.254	0
5	183	0.313	0
6	204	0.319	0
7	211	0.432	0
8	243	0.553	0.121
9	272	0.575	0.143
10	284	0.625	0.143
11	316	0.633	0.143
12	353	0.683	0.143
13	359	0.700	0.143
14	366	0.726	0.143
15	374	0.756	0.143
16	378	0.783	0.143
17	384	0.804	0.143

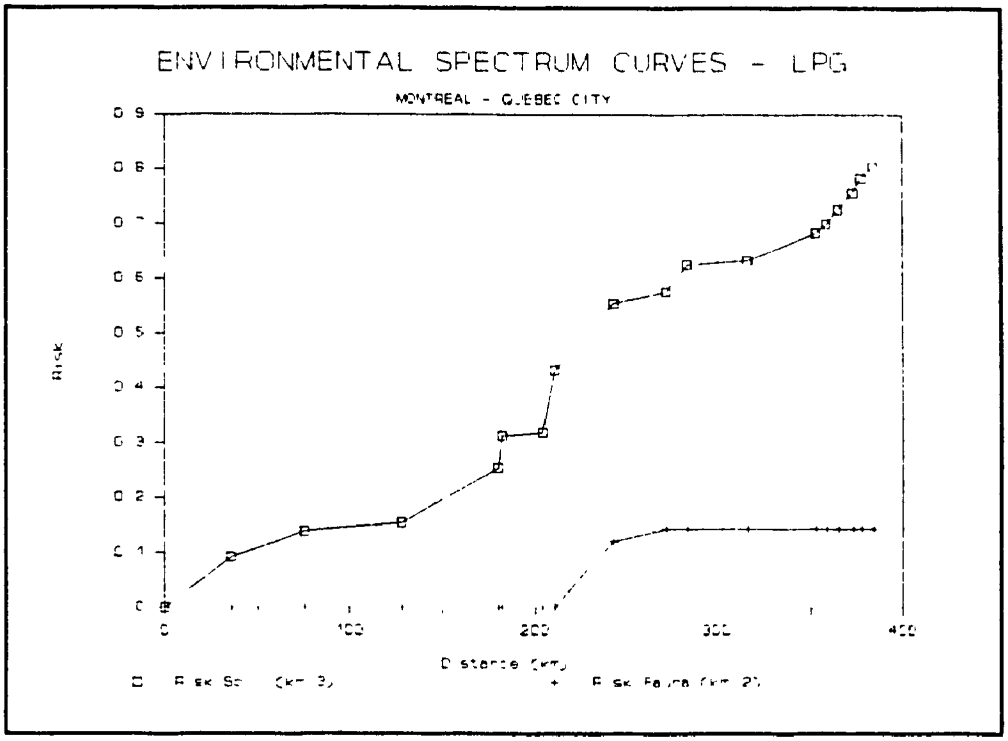

Figure B.4: ENVIRONMENTAL SPECTRUM CURVES (LPG)

Table B.16: RISK DISSIPATION (Sulphuric Acid)

LINK NO	NODE NO	DISTANCE (km)	CUMM. DIST. (km)	RISK (Soil, km³)
0	23	0	0	1.530
1	25	37	37	1.438
2	21	38	75	1.423
3	20	52	127	1.421
4	22	54	181	1.318
5	39	2	183	1.259
6	40	20	203	1.234
7	42	3	206	1.101
8	59	15	221	1.031
9	57	22	243	1.025
10	56	31	274	1.024
11	55	2	276	1.020
12	64	43	319	1.012
13	65	23	342	1.004
14	66	9	351	0.987
15	71	3	354	0.979
16	70	4	358	0.936
17	35	23	381	0.929
18	34	10	319	0.902
19	33	25	416	0.816
20	18	70	486	0.576
21	16	6	492	0.530
22	15	3	495	0.504
23	14	4	499	0.500
24	12	5	504	0.493
25	11	8	512	0.480
26	10	4	516	0.440
27	8	6	522	0

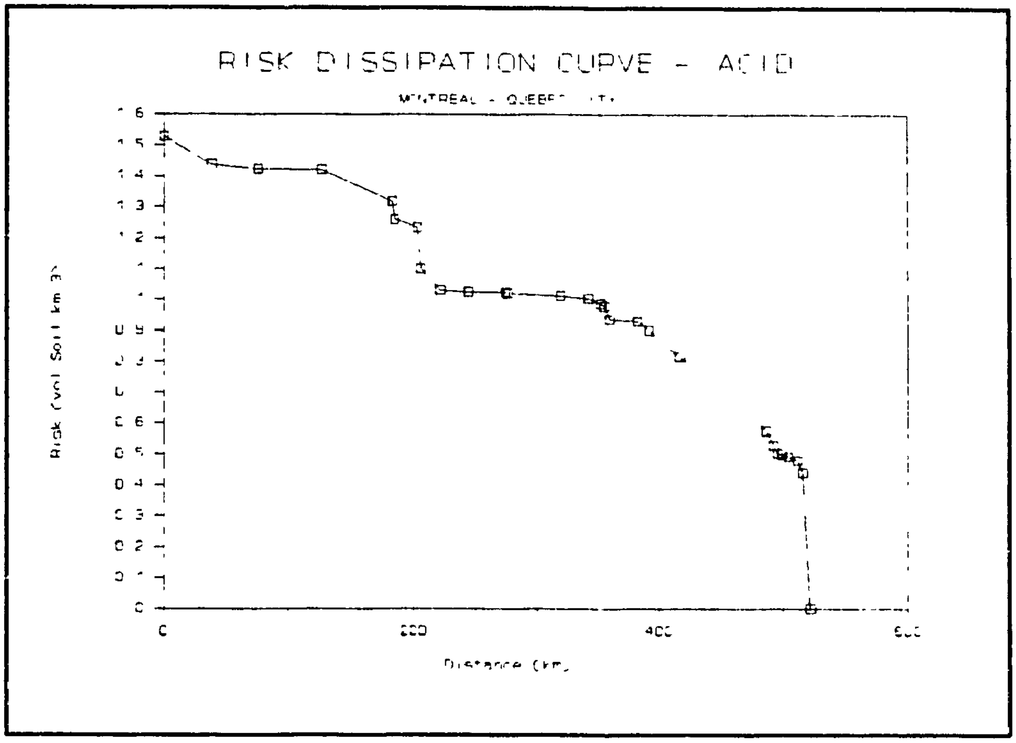

Figure B.5: RISK DISSIPATION CURVE (Sulphuric Acid)

Table B.17: RISK DISSIPATION (Chlorine)

LINK NO	NODE NO	DISTANCE (km)	CUMM. DIST. (km)	RISK (Fatalities)
0	23	0	0	32.701
1	25	37	37	26.570
2	21	38	75	26.403
3	20	52	127	26.369
4	22	54	181	24.738
5	34	2	183	24.494
6	36	20	203	24.460
7	37	3	206	24.285
8	38	5	211	22.199
9	39	6	217	21.040
10	62	50	267	20.826
11	63	6	273	20.791
12	66	23	296	20.756
13	71	3	299	20.734
14	65	4	303	20.712
15	35	23	326	20.371
16	34	10	336	20.315
17	33	25	361	20.106
18	18	70	431	18.686
19	16	6	437	18.095
20	15	3	440	17.163
21	14	4	444	16.572
22	12	5	449	15.612
23	11	4	453	11.175
24	10	4	457	6.738
25	8	6	463	0

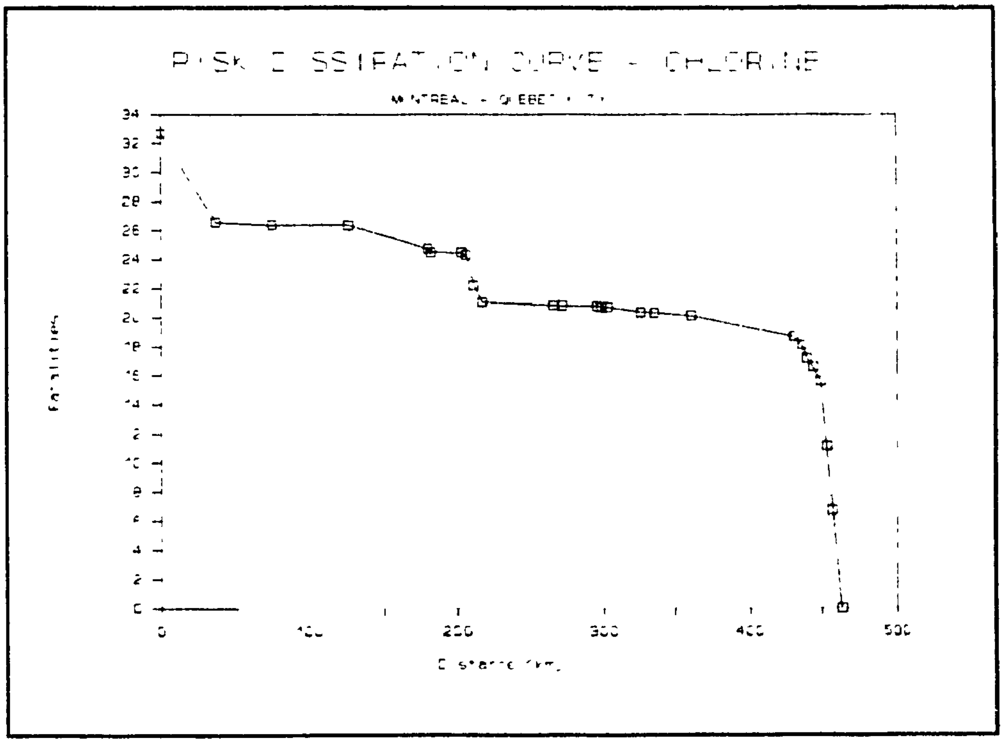

Figure B.6: RISK DISSIPATION CURVE (Chlorine)

O-D PAIR: MONTREAL - SHERBROOKE

Table B.18: RISK OPTIMIZATION

ROUTE	% RISK POPULATION	% RISK ENVIRONMENT	NORMALIZED RISK UNITS
R4	100	0	3.546
R5	75	25	3.205
R6	50	50	2.918
R_{min}	41	59	2.706
R7	25	75	2.869
R8	0	100	2.992

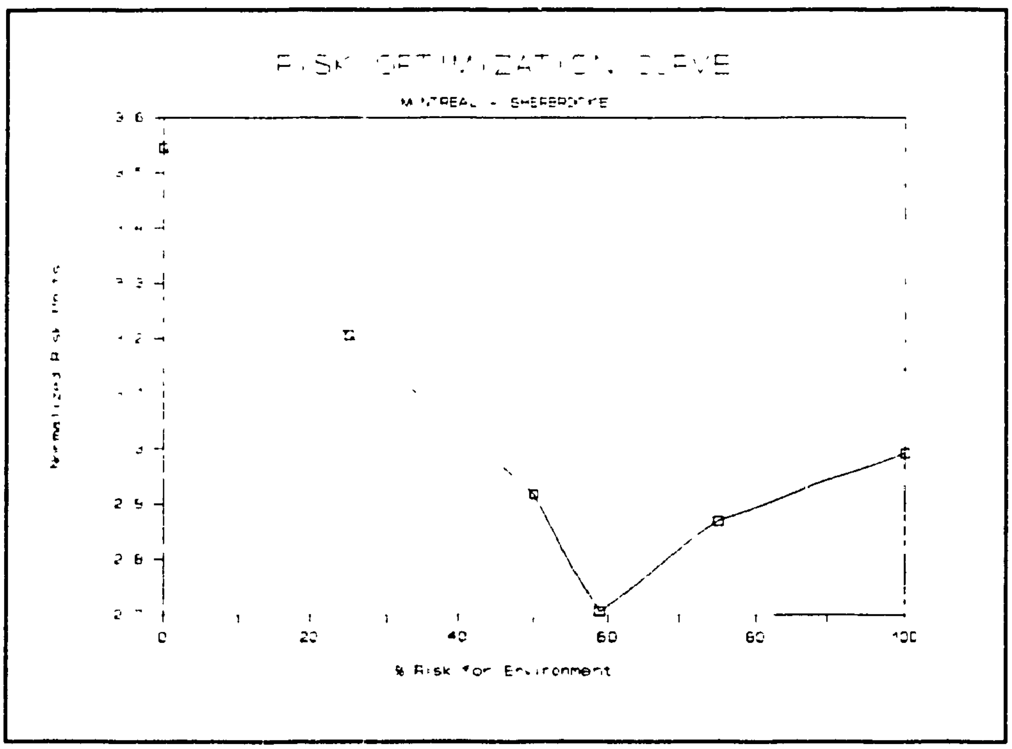

Figure B.7: RISK OPTIMIZATION CURVE

Table B.19: RISK DISSIPATION (LPG)

LINK NO	NODE NO	DISTANCE (km)	CUMM.DIS. (km)	T.NORM RISK UNITS	RISK POP (NORM UNITS)	RISK ENV (NORM UNITS)
0	23	0	0	2.706	1.109	1.597
1	25	32	32	1.959	0.803	1.156
2	21	38	70	1.886	0.773	1.113
3	20	52	122	1.816	0.745	1.071
4	13	7	129	1.582	0.649	0.933
5	41	4	133	1.473	0.604	0.869
6	46	26	159	1.109	0.455	0.654
7	47	3	162	1.054	0.432	0.622
8	49	27	189	0.847	0.347	0.500
9	50	5	194	0.257	0.105	0.152
10	48	38	232	0.190	0.078	0.112
11	57	47	279	0.184	0.075	0.109
12	56	3	282	0.178	0.073	0.105
13	55	3	285	0.146	0.060	0.086
14	58	7	292	0.103	0.042	0.061
15	59	9	301	0.060	0.025	0.035
16	45	5	306	0	0	0

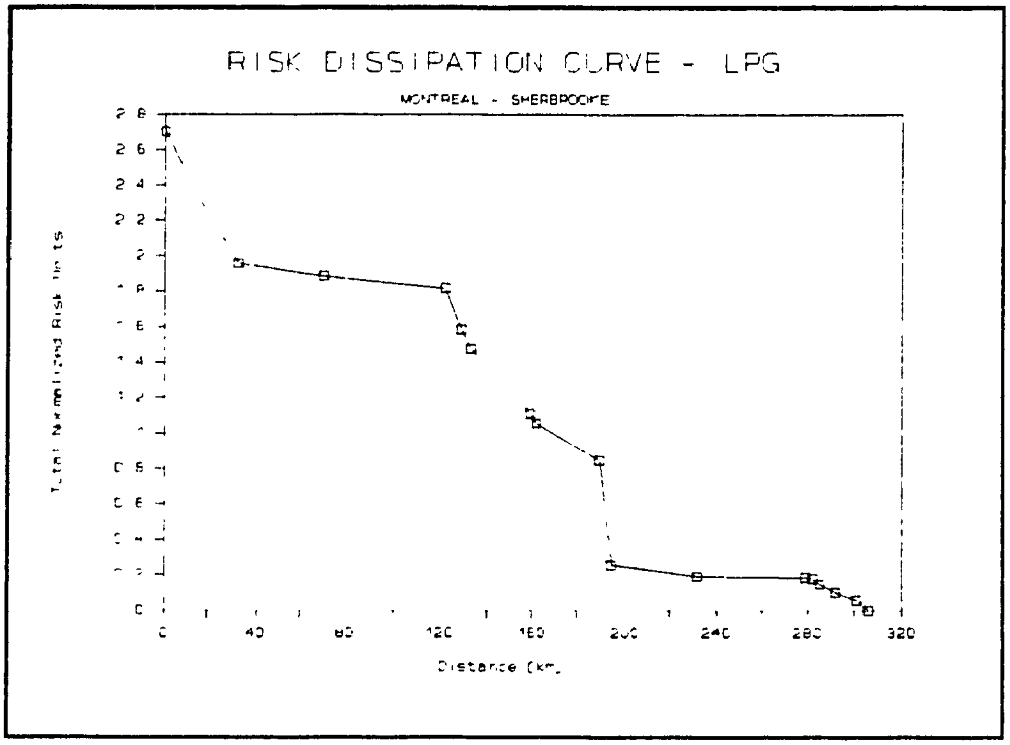

Figure B.8: TOTAL RISK DISSIPATION CURVE (LPG)

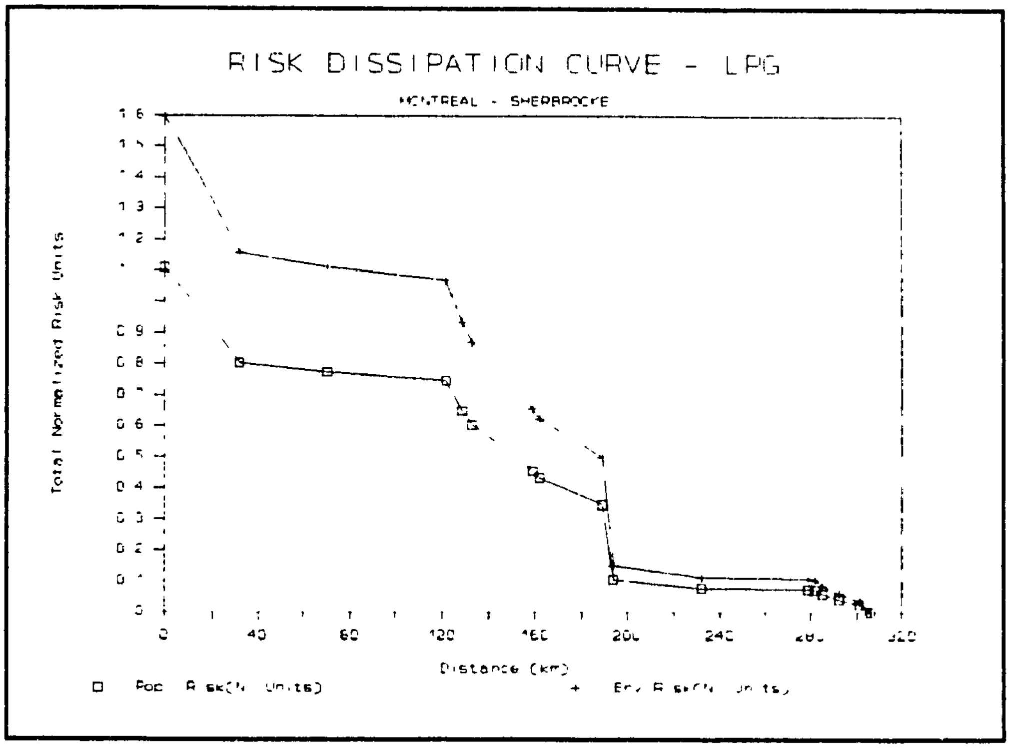

Figure B.9: INDIVIDUAL RISK DISSIPATION CURVES (LPG)

Table B.20: ENVIRONMENTAL RISK (LPG)

LINK NO	CUMM. DIST. (km)	CUMM. RISK (Soil km^3)	CUMM. RISK (Farms km^2)
0	0	0	0
1	32	0.092	0
2	70	0.139	0
3	122	0.154	0
4	129	0.184	0
5	133	0.193	0
6	159	0.204	0
7	162	0.211	0
8	189	0.255	0
9	194	0.268	0
10	234	0.282	0.013
11	279	0.285	0.027
12	282	0.286	0.027
13	285	0.287	0.027
14	292	0.293	0.027
15	301	0.299	0.027
16	306	0.302	0.027

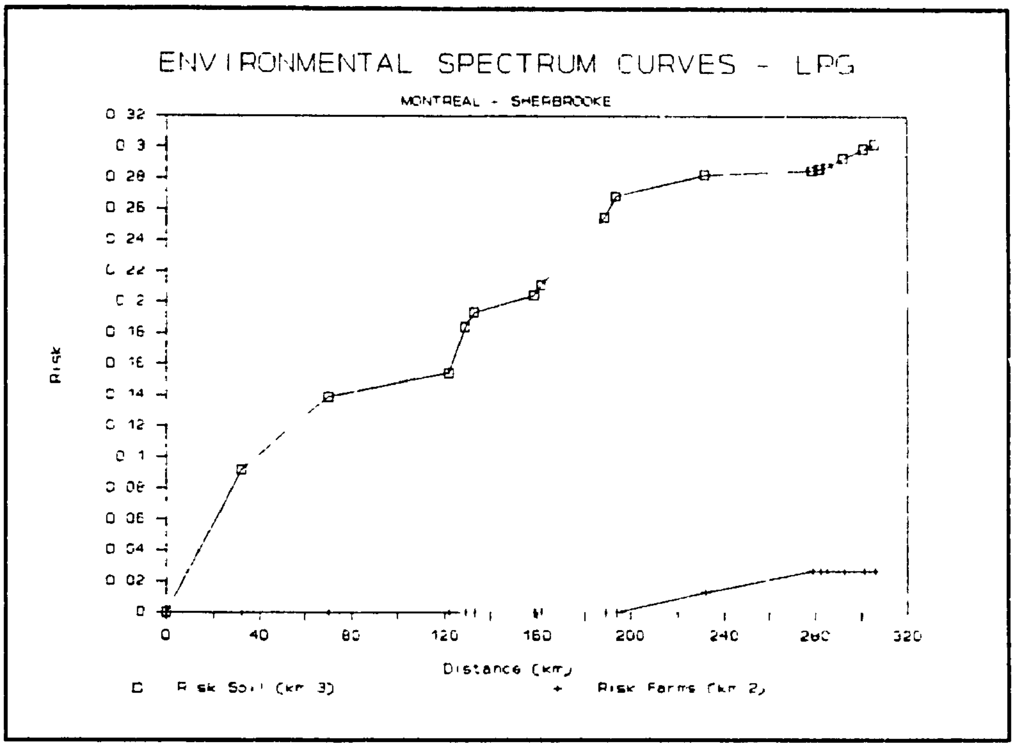

Figure B.10: ENVIRONMENTAL SPECTRUM CURVES (LPG)

Table B.21: RISK DISSIPATION (Sulphuric Acid)

LINK NO	NODE NO	DISTANCE (km)	CUMM. DIST. (km)	RISK (Soil, km^3)
0	23	0	0	0.331
1	25	32	32	0.239
2	21	38	70	0.223
3	20	52	122	0.221
4	38	54	176	0.118
5	39	3	179	0.113
6	40	6	185	0.089
7	42	7	192	0.083
8	47	15	207	0.051
9	51	22	229	0.035
10	56	31	260	0.022
11	55	2	262	0.021
12	57	48	310	0.015
13	54	5	315	0.012
14	65	3	318	0.010
15	58	7	325	0.004
16	59	9	334	0.002
17	45	5	339	0

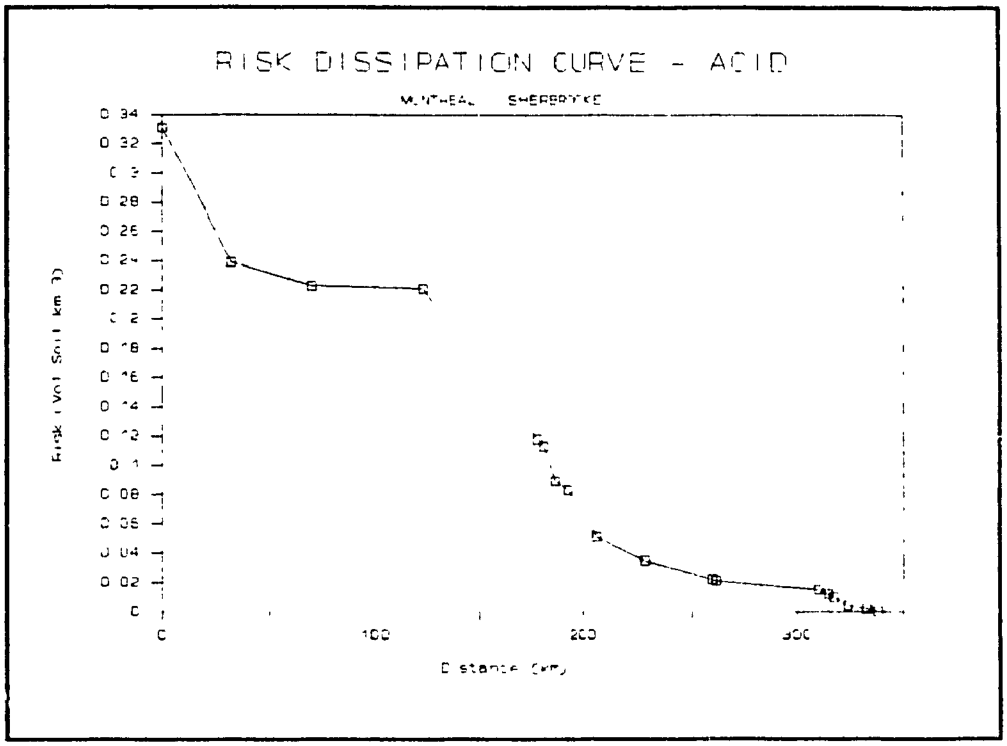

Figure B.11: RISK DISSIPATION CURVE (Sulphuric Acid)

Table B.22: RISK DISSIPATION (Chlorine Gas)

LINK NO	NODE NO	DISTANCE (km)	CUMM. DIST. (km)	RISK (Fatalities)
0	23	0	0	13.310
1	25	32	32	7.180
2	21	38	70	7.012
3	20	52	122	6.978
4	13	7	129	5.156
5	24	5	134	4.196
6	69	29	163	4.144
7	67	32	195	3.786
8	68	29	224	3.586
9	75	7	231	3.448
10	28	13	244	2.863
11	29	3	247	2.836
12	31	1	248	2.827
13	32	12	260	2.718
14	34	20	280	2.660
15	33	25	305	2.451
16	18	70	375	1.031
17	17	4	379	1.007
18	3	32	411	0.954
19	2	21	432	0.606
20	1	23	455	0.479
21	41	72	527	0.385
22	42	26	553	0.301
23	43	54	607	0.180
24	45	6	613	0

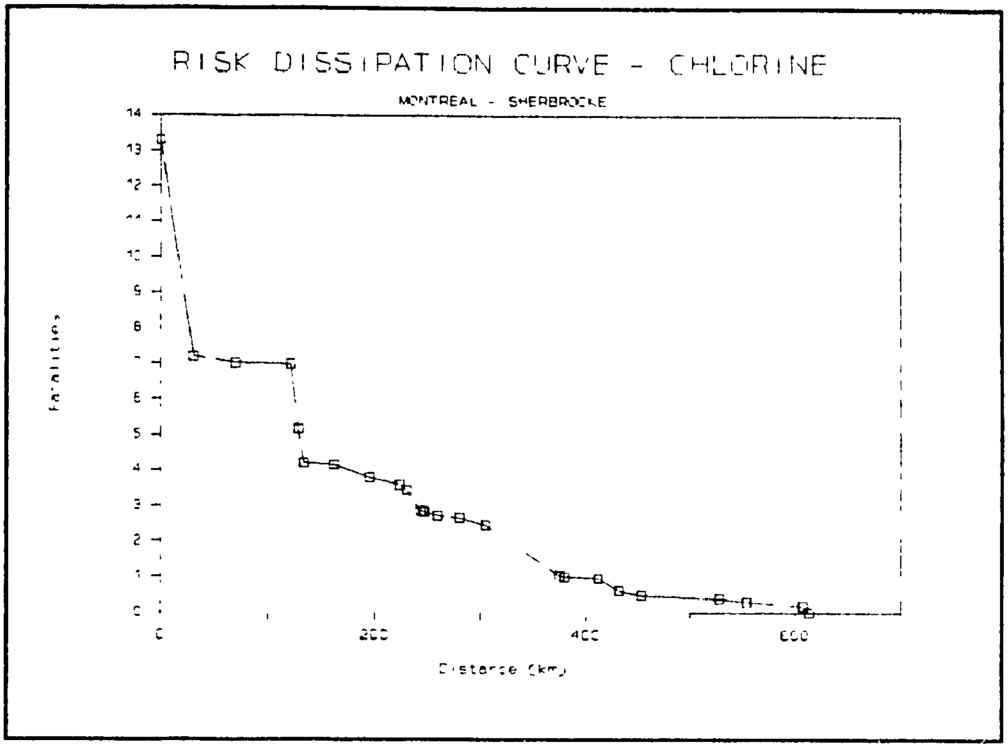

Figure B.12: RISK DISSIPATION CURVE (Chlorine Gas)

O-D PAIR: TROIS-RIVIÉRES - QUEBEC CITY

Table B.23: Risk Optimization

ROUTE	% RISK POPULATION	%RISK ENVIRONMENT	NORMALIZED RISK UNITS
R4	100	0	2.454
R5	75	25	2.161
R6	50	50	1.718
R7	25	75	1.609
R8	0	100	1.792

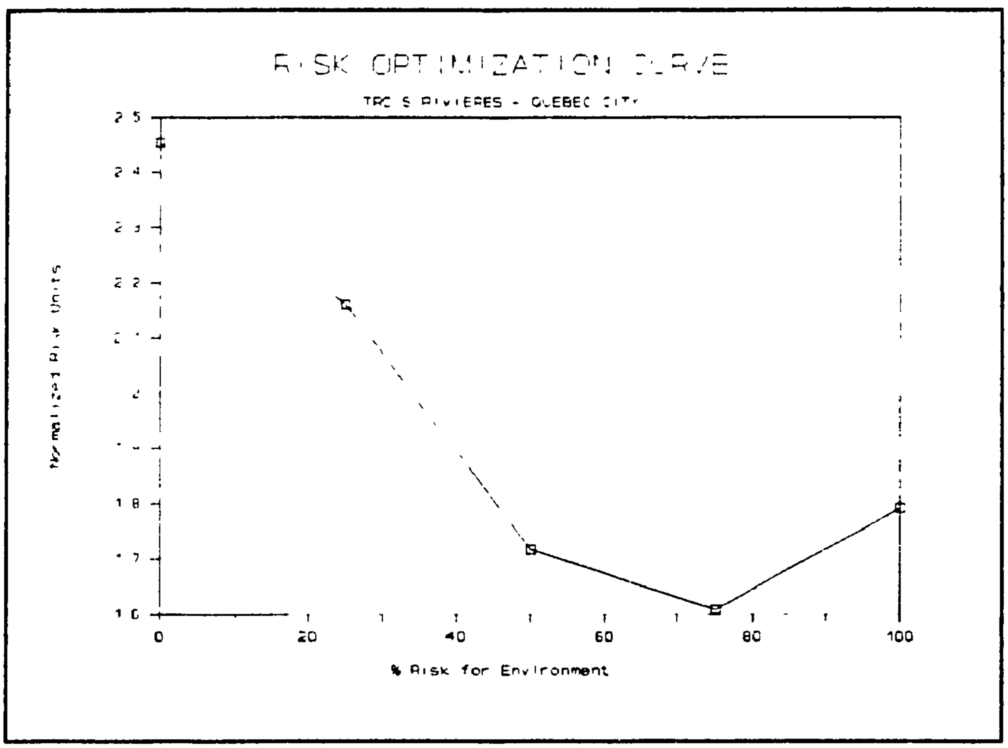

Figure B.13: RISK OPTIMIZATION CURVE

Table B.24: Risk Dissipation (LPG)

Link No	Node No	Distance (km)	Cumm. Dis. (km)	T. Norm. Risk Units	Risk Pop. (Norm Units)	RiskEnv (Norm Units)
1	26	0	0	1.543	0.633	0.91
2	25	9	9	1.419	0.582	0.837
3	21	38	47	1.346	0.552	0.794
4	20	52	99	1.331	0.546	0.789
5	13	7	106	1.156	0.479	0.682
6	11	8	114	0.772	0.317	0.455
7	10	4	118	0.465	0.191	0.274
8	8	6	124	0	0	0

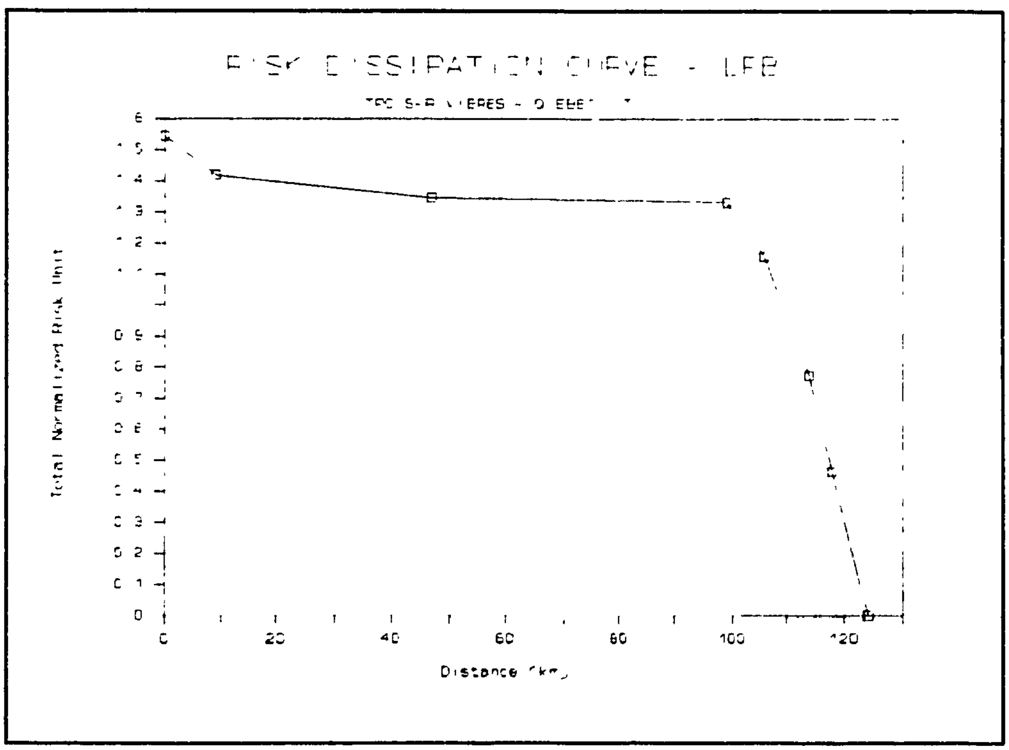

Figure B.14: TOTAL RISK DISSIPATION CURVE (LPG)

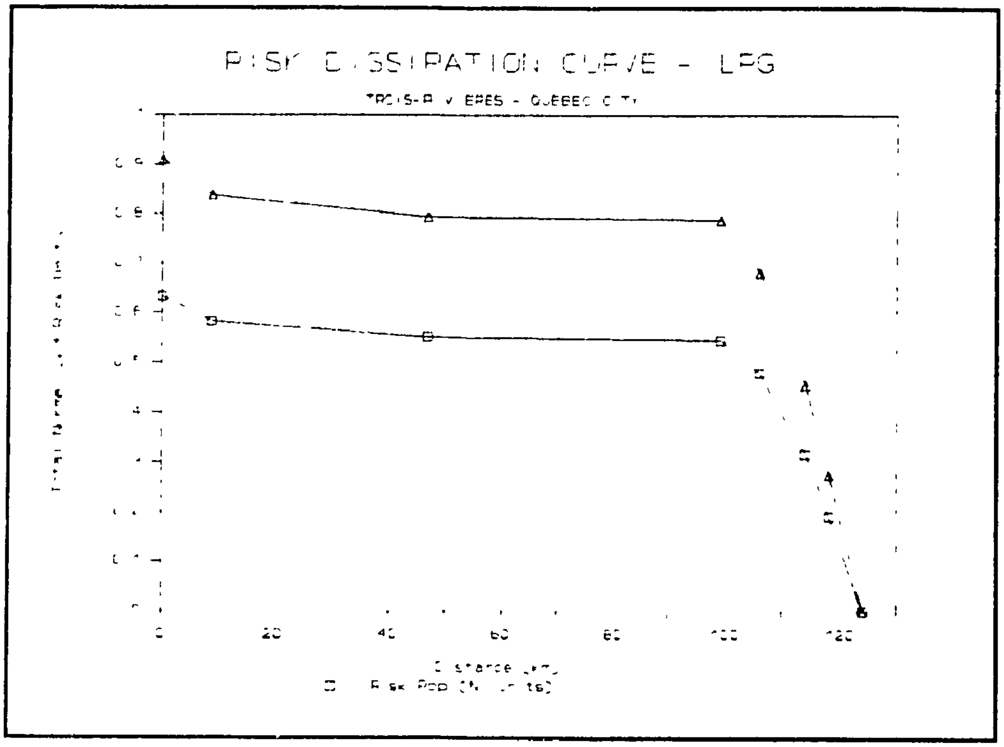

Figure B.15: INDIVIDUAL RISK DISSIPATION CURVES (LPG)

Table B.25: Environmental risk (LPG)

Link No	Cumm. Dist. (km)	Cumm. Risk Soil (km^3)	Cumm. Risk Farms (km^2)	Cumm. Risk Fauna (km^2)
0	0	0	0	0
1	9	0.017	0	0
2	47	0.064	0.017	0.047
3	99	0.079	0.017	0.047
4	106	0.109	0.017	0.047
5	114	0.139	0.017	0.047
6	118	0.166	0.017	0.047
7	124	0.187	0.017	0.047

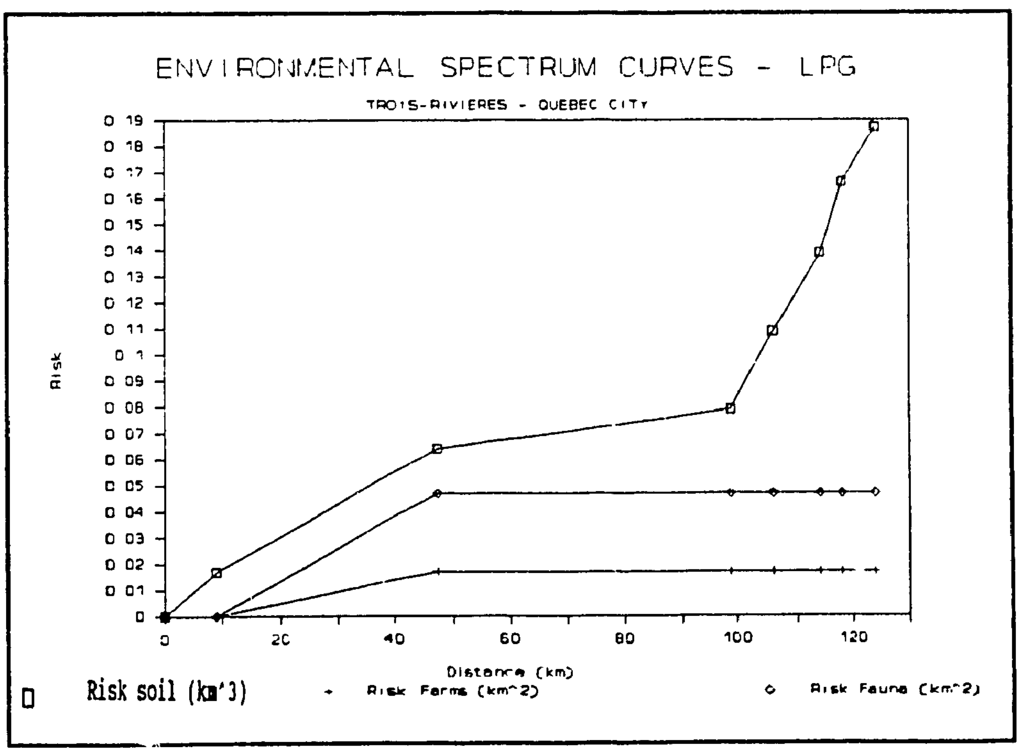

Figure B.16: ENVIRONMENTAL SPECTRUM CURVES (LPG)

Table B.26: Risk Dissipation (Sulphuric Acid)

Link No	Node No	Distance (km)	Cumm. Dis. (km)	Risk Soil (km^3)
1	26	0	0	0.1025
2	25	9	9	0.0855
3	21	38	47	0.0700
4	20	52	99	0.0680
5	13	7	106	0.0510
6	11	8	114	0.0340
7	10	4	118	0.0205
8	8	6	124	0.0000

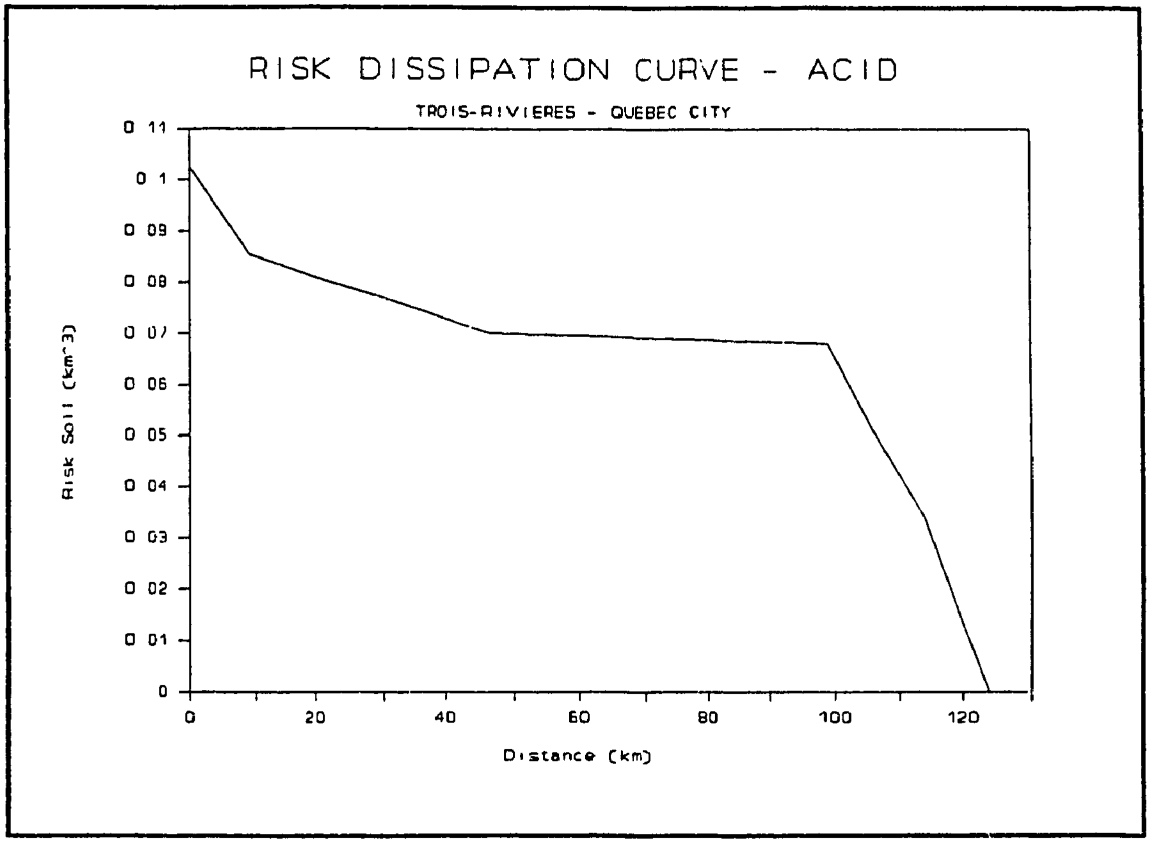

Figure B.17: Risk Dissipation Curve (Sulphuric Acid)

Table B.27: Environmental risk (Sulphuric Acid)

Link No	Cumm. Dist. (km)	Cumm. Risk Soil (km^3)	Cumm. Risk Farms (km^2)	Cumm. Risk Fauna (km^2)
0	0	0	0	0
1	9	0.017	0	0
2	47	0.033	0.017	0.016
3	99	0.035	0.017	0.016
4	106	0.052	0.017	0.016
5	114	0.069	0.017	0.016
6	118	0.100	0.017	0.016
7	124	0.144	0.017	0.016

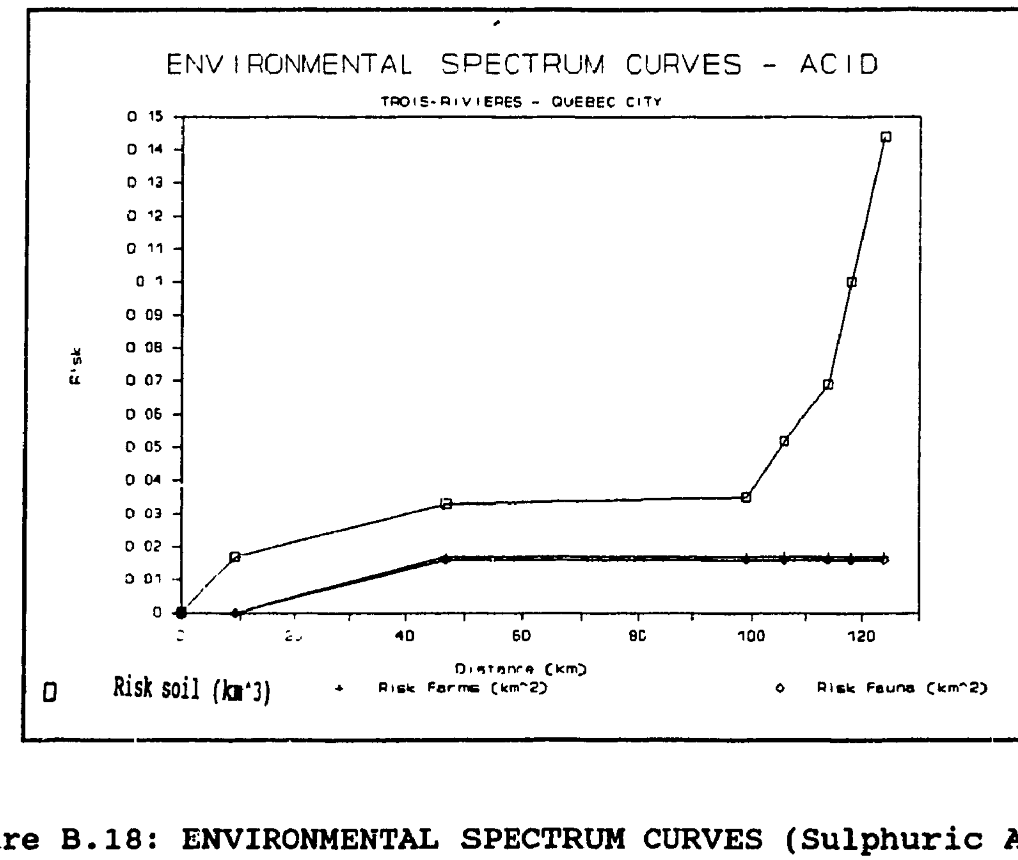

Figure B.18: ENVIRONMENTAL SPECTRUM CURVES (Sulphuric Acid)

Table B.28: Risk Dissipation (Chlorine)

Link No.	Node No.	Distance (km)	Cumm. Dist. (km)	Risk (fatalities)
1	26	0	0	19.216
2	28	2	2	18.729
3	29	3	5	18.702
4	31	1	6	18.693
5	30	10	16	18.664
6	19	104	120	18.292
7	15	9	129	17.163
8	14	4	133	16.572
9	12	5	138	15.612
10	11	4	142	11.175
11	10	4	146	6.738
12	8	6	152	

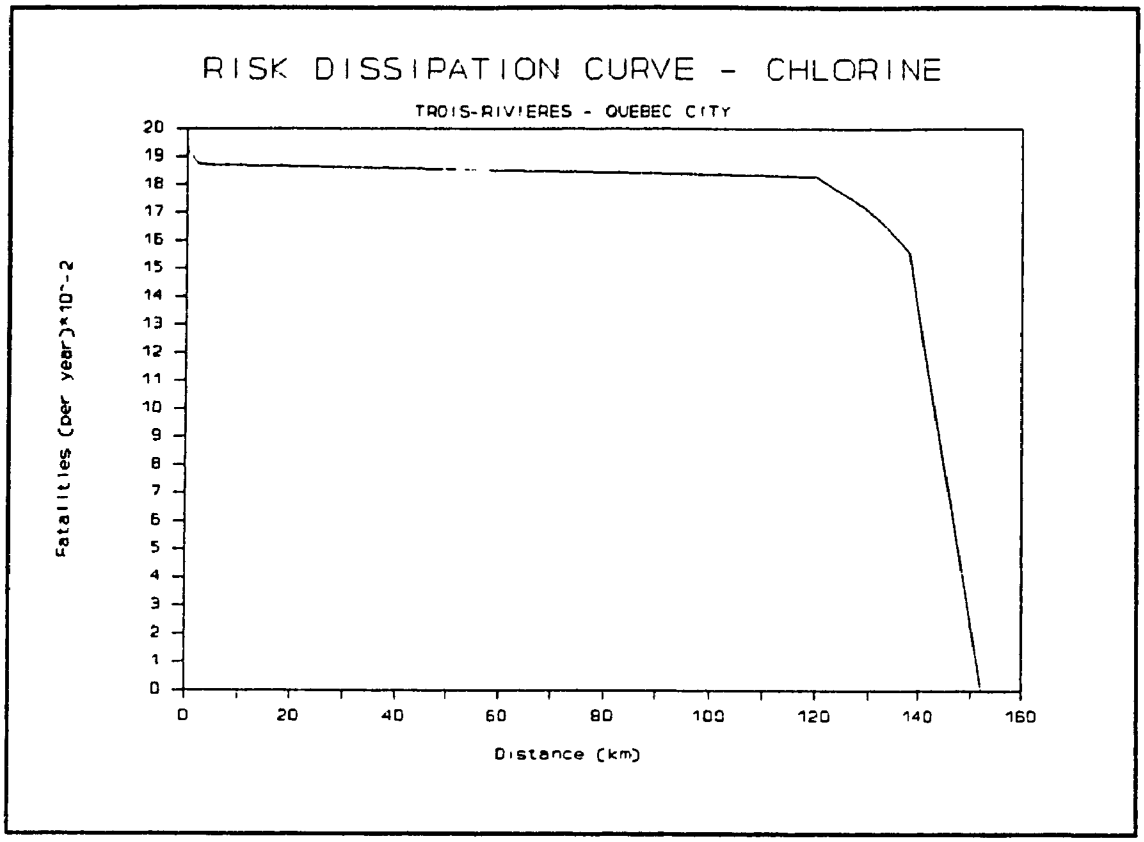

Figure B.19: Risk Dissipation Curve (Chlorine)

O-D PAIR: DRUMMONDVILLE - QUEBEC CITY

Table B.29: Risk Optimization

ROUTE	% RISK POPULATION	%RISK ENVIRONMENT	NORMALIZED RISK UNITS
R4	100	0	2.448
R5	75	25	2.411
R6	50	50	2.344
R7	25	75	2.19
R8	0	100	2.251

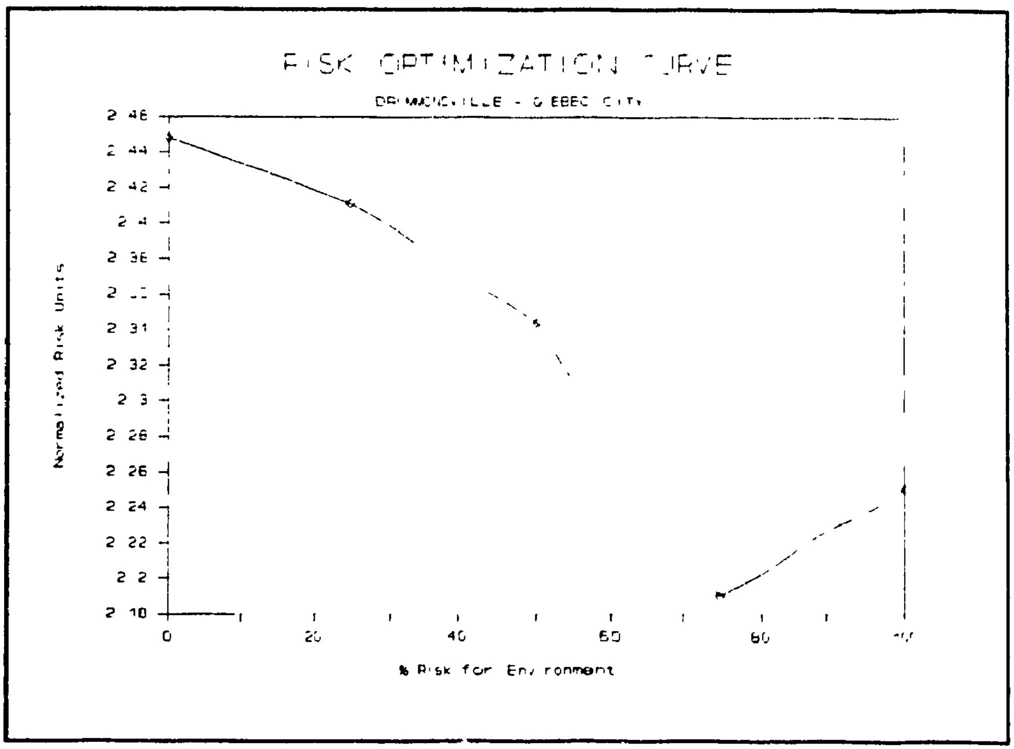

Figure B.20: RISK OPTIMIZATION CURVE

Table B.30: Risk Dissipation (LPG)

Link No	Node No	Distance (km)	Cumm. Dis. (km)	T. Norm. Risk Units	Risk Pop. (Norm Units)	RiskEnv (Norm Units)
1	64	0	0	2.099	0.861	1.238
2	65	3	3	1.976	0.81	1.166
3	66	33	36	1.898	0.778	1.12
4	29	43	79	1.616	0.663	0.953
5	28	3	82	1.588	0.651	0.937
6	26	2	84	1.543	0.633	0.91
7	25	9	93	1.419	0.582	0.837
8	21	38	131	1.346	0.552	0.794
9	20	52	183	1.331	0.546	0.785
10	13	7	190	1.156	0.474	0.682
11	11	8	198	0.772	0.317	0.455
12	10	4	202	0.465	0.191	0.274
13	8	6	208	0	0	0

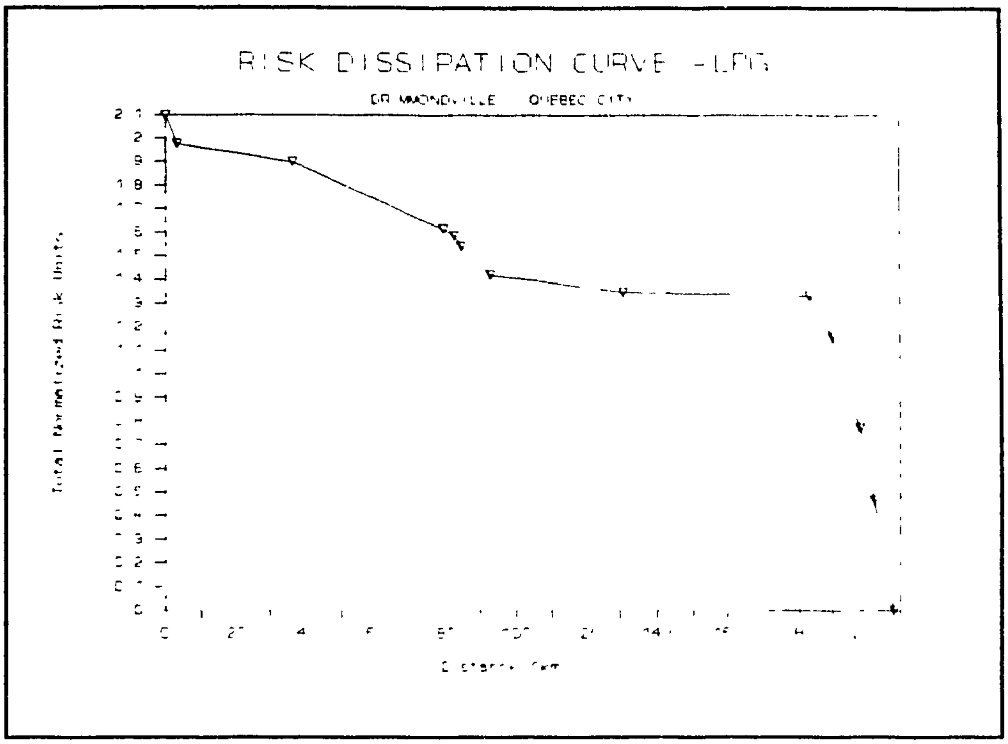

Figure B.21: TOTAL RISK DISSIPATION CURVE (LPG)

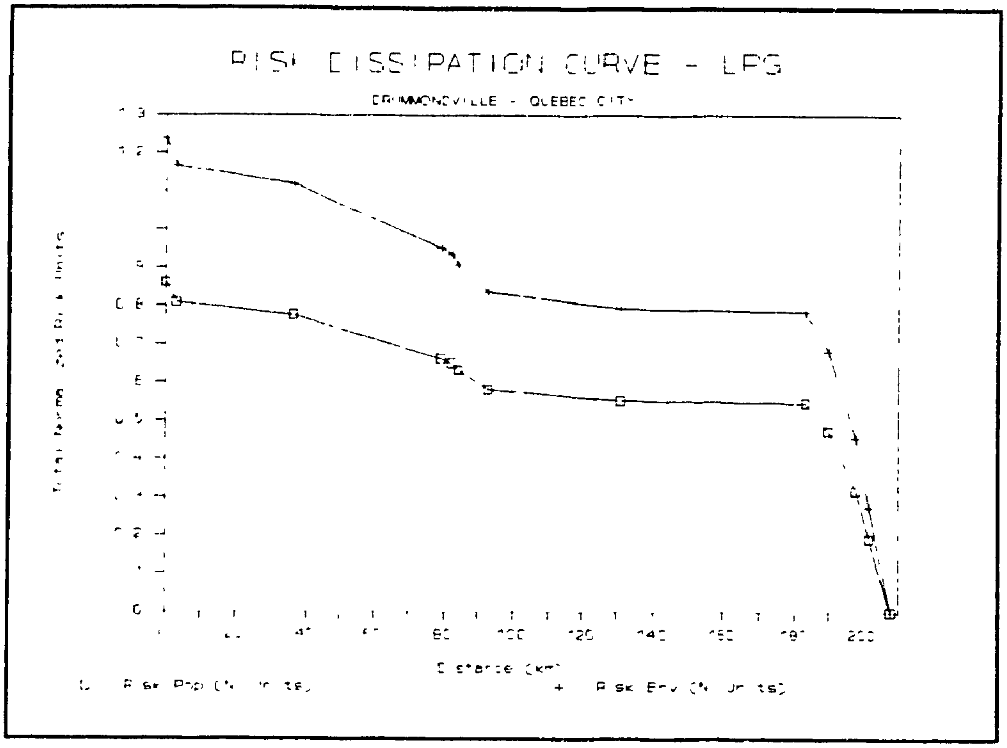

Figure B.22: INDIVIDUAL RISK DISSIPATION CURVES (LPG)

Table B.31: Environmental Risk (LPG)

Link No	Cumm. Dist. (km)	Cumm. Risk Soil (km^3)	Cumm. Risk Farms (km^2)	Cumm. Risk Fauna (km^2)
0	0	0	0	0
1	3	0.021	0	0
2	36	0.039	0	0
3	79	0.078	0.039	0
4	82	0.084	0.039	0
5	84	0.088	0.039	0
6	93	0.105	0.039	0
7	131	0.152	0.086	0
8	183	0.167	0.086	0.015
9	190	0.197	0.086	0.015
10	198	0.227	0.086	0.015
11	202	0.254	0.086	0.015
12	208	0.275	0.086	0.015

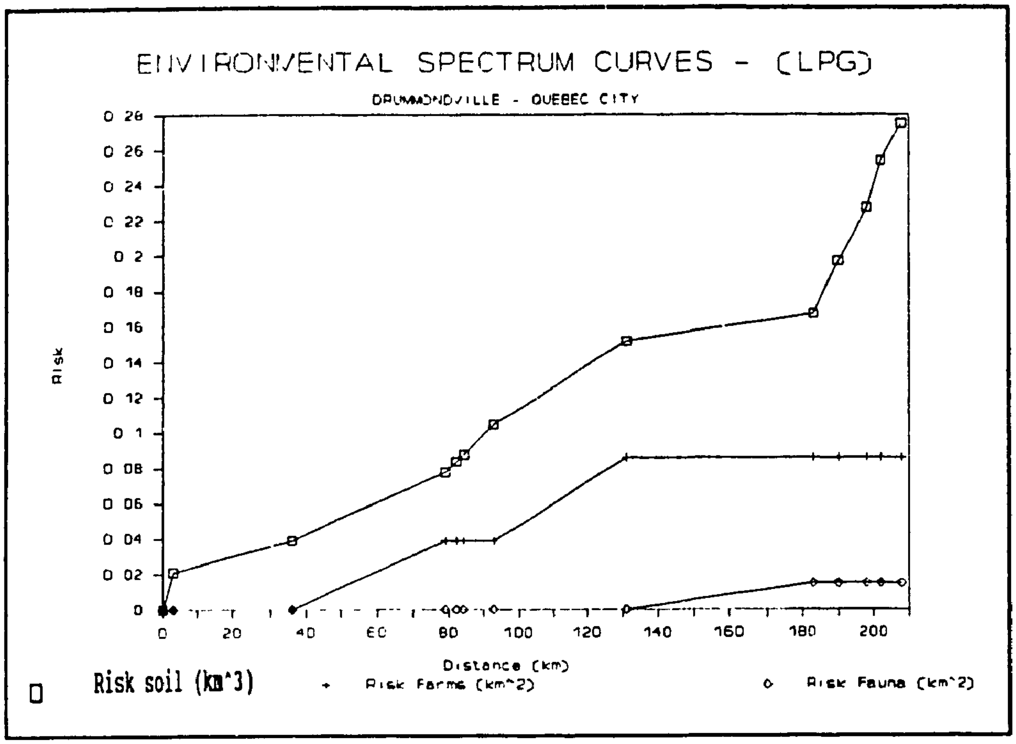

Figure B.23: Environmental Spectrum Curves (LPG)

Table B.32: Risk Dissipation (Sulphuric Acid)

Link No	Node No	Distance (km)	Cumm. Dis. (km)	Risk Soil (km^3)
1	64	0	0	0.175
2	65	3	3	0.167
3	66	33	36	0.15
4	29	43	79	0.1125
5	28	3	82	0.1065
6	26	2	84	0.1025
7	25	9	93	0.0855
8	21	38	131	0.07
9	20	52	183	0.068
10	13	7	190	0.051
11	11	8	198	0.034
12	10	4	202	0.0205
13	8	6	208	

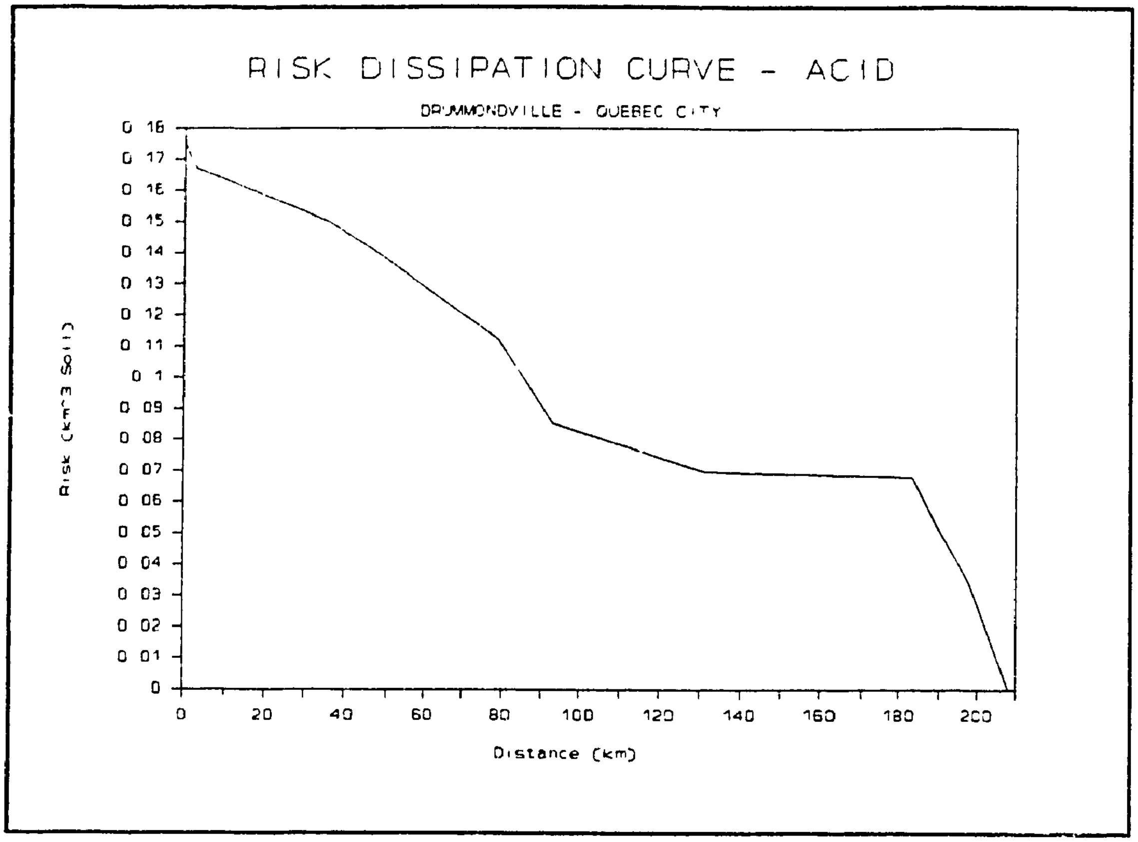

Figure B.24: Risk Dissipation Curve (Sulphuric Acid)

Table B.33: Environmental Risk (Sulphuric Acid)

Link No	Cumm. Dist. (km)	Cumm. Risk Soil (km^3)	Cumm. Risk Farms (km^2)	Cumm. Risk Fauna (km^2)
0	0	0	0	0
1	3	0.008	0	0
2	36	0.025	0	0
3	79	0.063	0.038	0
4	82	0.069	0.038	0
5	84	0.073	0.038	0
6	93	0.090	0.038	0
7	131	0.105	0.053	0
8	183	0.107	0.053	0.002
9	190	0.124	0.053	0.002
10	198	0.141	0.053	0.002
11	202	0.172	0.053	0.002
12	208	0.216	0.053	0.002

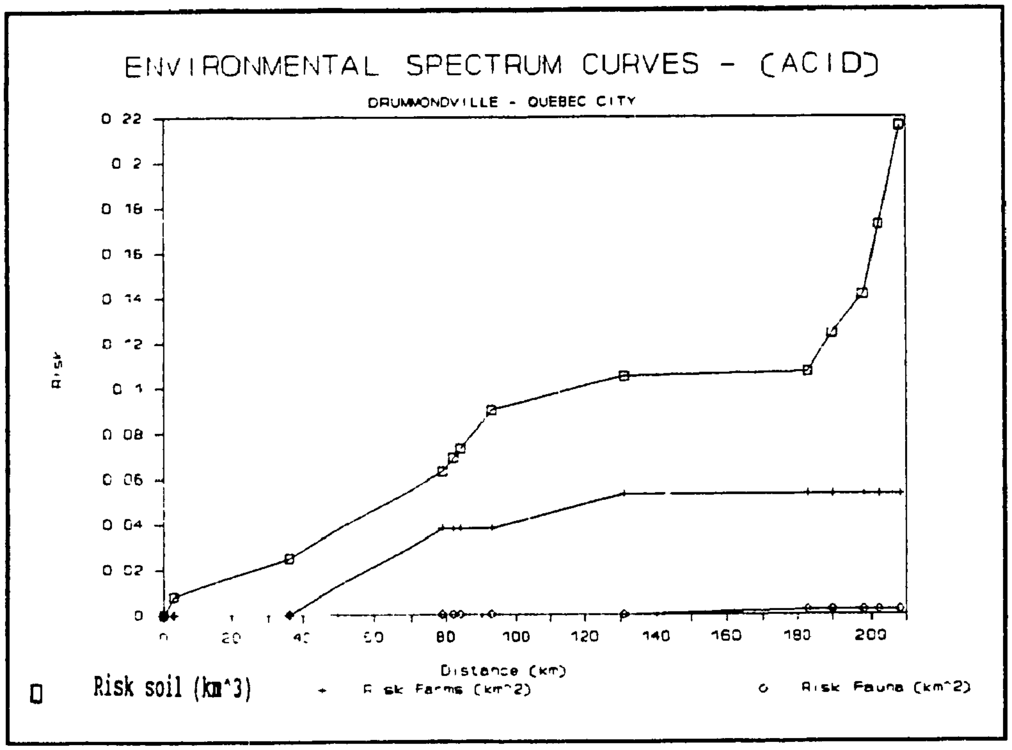

Figure B.25: Environmental Spectrum Curves (Sulphuric Acid)

Table B.34: Risk Dissipation (Chlorine)

Link No.	Node No.	Distance (km)	Cumm. Dist. (km)	Risk (fatalities)
1	64	0	0	19.172
2	36	48	48	18.894
3	34	20	68	18.86
4	32	20	88	18.802
5	31	12	100	18.693
6	30	10	110	18.664
7	19	104	214	18.292
8	15	9	223	17.163
9	14	4	227	16.572
10	12	5	232	15.612
11	11	4	236	11.175
12	10	4	240	6.783
13	8	6	246	

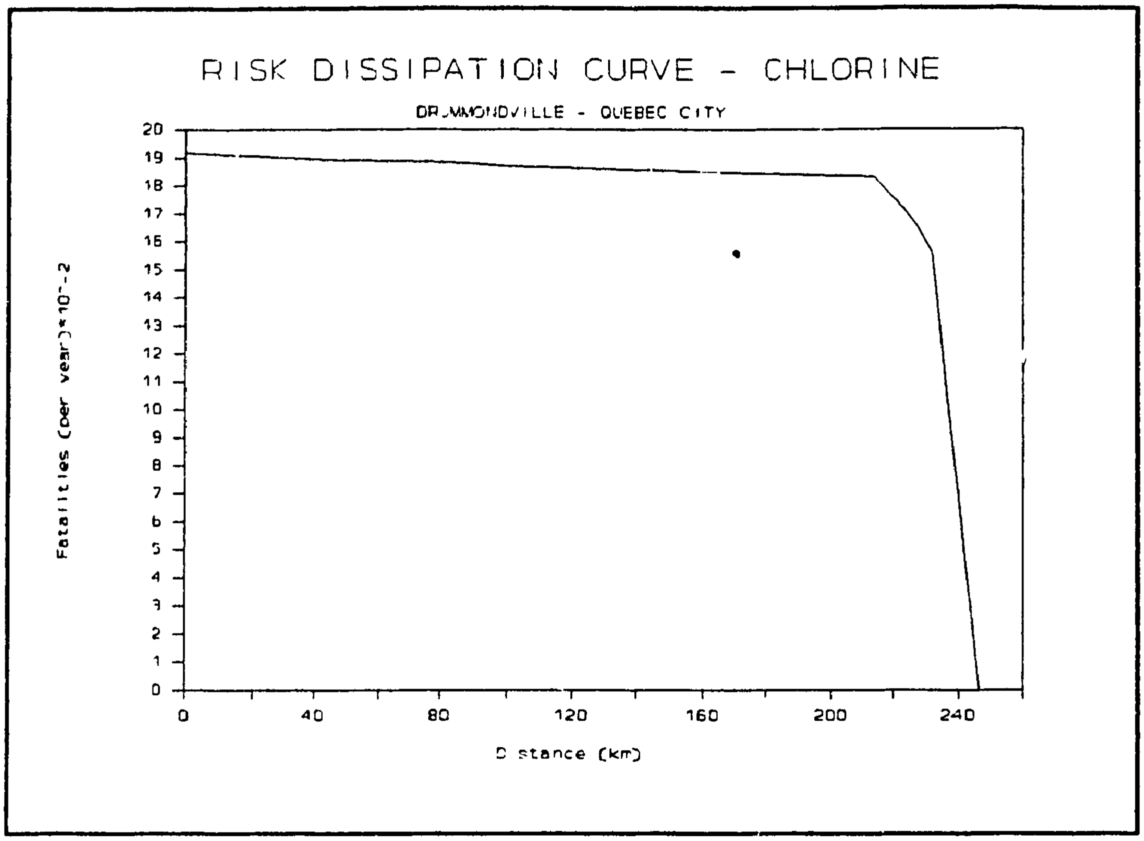

Figure B.26: Risk Dissipation Curve (Chlorine)

APPENDIX - C

COMPUTER PROGRAMS & DISPERSION MODELS

The computer programs developed in this thesis are listed in this appendix. All the programs are written in Quick Basic. These programs are grouped into two files, namely, [MINROUTE] for minimum exposure and minimum risk routes and, [DISMODELS] for dispersion models.

In the first section, a numerical example of a sample network is solved using Floyd's algorithm. The computer program listing and output are also attached. In the next section, equations and flow charts for spill model for LPG is presented. Computer listings and outputs are also attached. The computer models are one component of the network risk analysis models developed by the Institute for Risk Research [19].

LIST OF FIGURE AND TABLES

SECTION I

Numerical Example Using Floyd's Algorithm

For the following simple network we determine the minimum path tree.

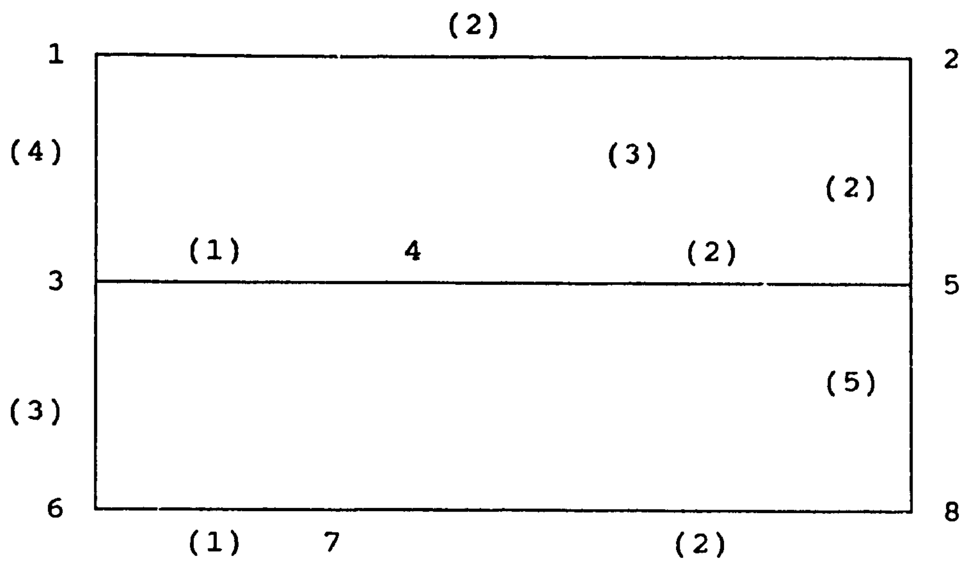

Figure C.1: Simple network

The first step is to tabulate the skim tree and backnode matrix.

Table C.1: Skim tree matrix

j / i	1	2	3	4	5	6	7	8
1	0	2	4	999	999	999	999	999
2	2	0	999	3	2	999	999	999
3	4	999	0	1	999	3	999	999
4	999	3	1	0	2	999	4	999
5	999	2	999	2	0	999	999	5
6	999	999	3	999	999	0	1	999
7	999	999	999	4	999	1	0	2
8	999	999	999	999	5	999	2	0

Table C.2: Back node matrix

j / i	1	2	3	4	5	6	7	8
1	1	1	1	1	1	1	1	1
2	2	2	2	2	2	2	2	2
3	3	3	3	3	3	3	3	3
4	4	4	4	4	4	4	4	4
5	5	5	5	5	5	5	5	5
6	6	6	6	6	6	6	6	6
7	7	7	7	7	7	7	7	7
8	8	8	8	8	8	8	8	8

We recall that

```
For K = 1,N          SUM = LT(I,K) + LT(K,J)
For I = 1,N          IS SUM < LT(I,J)
For J = 1,N          IF YES, LT(I,J) = SUM;
                             P(I,J)=P(K,J)
                     IF NO, BYPASS
```

Calculations

For K = 1

```
              SUM = LT(I,1) + LT(1,J) < LT(I,J)

LT(1,1) + LT(1,1) = 0 + 0     = 0   < LT(1,1) -> NO -> BYPASS
LT(1,1) + LT(1,2) = 0 + 2     = 2   < LT(1,2) -> NO -> BYPASS
LT(1,1) + LT(1,3) = 0 + 4     = 4   < LT(1,3) -> NO -> BYPASS
LT(1,1) + LT(1,4) = 0 + 999   = 999 < LT(1,4) -> NO -> BYPASS
LT(1,1) + LT(1,5) = 0 + 999   = 999 < LT(1,5) -> NO -> BYPASS
LT(1,1) + LT(1,6) = 0 + 999   = 999 < LT(1,6) -> NO -> BYPASS
LT(1,1) + LT(1,7) = 0 + 999   = 999 < LT(1,7) -> NO -> BYPASS
LT(1,1) + LT(1,8) = 0 + 999   = 999 < LT(1,8) -> NO -> BYPASS

              ------------------------------

LT(2,1) + LT(1,1) = 2 + 0 = 2 < LT(2,1) = 2   -> NO -> BYPASS
LT(2,1) + LT(1,2) = 2 + 2 = 4 < LT(2,2) = 0   -> NO -> BYPASS
LT(2,1) + LT(1,3) = 2 + 4 = 6 < LT(2,3) = 999 -> YES
                                              LT(2,3) = 6
                                      P(2,3) = P(1,3) = 1
LT(2,1) + LT(1,4) = 2 + 999 = 1001<LT(2,4) = 3 -> NO -> BYPASS
LT(2,1) + LT(1,5) = 2 + 999 = 1001<LT(2,5) = 2 -> NO -> BYPASS
LT(2,1) + LT(1,6) = 2 + 999 = 1001<LT(2,6)=999 -> NO -> BYPASS
LT(2,1) + LT(1,7) = 2 + 999 = 1001<LT(2,7)=999 -> NO -> BYPASS
LT(2,1) + LT(1,8) = 2 + 999 = 1001<LT(2,8)=999 -> NO -> BYPASS

              --------------------------------

LT(3,1) + LT(1,1) = 4 + 0   = 4 < LT(3,1) = 4   -> NO -> BYPASS
LT(3,1) + LT(1,2) = 4 + 2   = 6 < LT(3,2) = 999 -> YES
                                              LT(3,2) = 6
                                      P(2,3) = P(1,2) = 1
LT(3,1) + LT(1,3) = 4 + 4   = 8 < LT(3,3) = 0   -> NO -> BYPASS
LT(3,1) + LT(1,4) = 4 + 999 = 1003<LT(3,4)= 1   -> NO -> BYPASS
LT(3,1) + LT(1,5) = 4 + 999 = 1003<LT(3,5)=999  -> NO -> BYPASS
LT(3,1) + LT(1,6) = 4 + 999 = 1003<LT(3,6)= 3   -> NO -> BYPASS
LT(3,1) + LT(1,7) = 4 + 999 = 1003<LT(3,7)=999  -> NO -> BYPASS
LT(3,1) + LT(1,8) = 4 + 999 = 1003<LT(3,8)=999  -> NO -> BYPASS

              -----------------------------------
```

Since LT(4,1) = LT(5,1) = LT(6,1) = LT(7,1) = LT(8,1) = 999, the rest of the nodes are bypassed. After the first cycle, the skim tree matrix and backnode matrix have the following values.

Table C.3: Skim tree matrix $LT(I,J)_1$

j / i	1	2	3	4	5	6	7	8
1	0	2	4	999	999	999	999	999
2	2	0	6	3	2	999	999	999
3	4	6	0	1	999	3	999	999
4	999	3	1	0	2	999	4	999
5	999	2	999	2	0	999	999	5
6	999	999	3	999	999	0	1	999
7	999	999	999	4	999	1	0	2
8	999	999	999	999	5	999	2	0

Table C.4: Back node matrix $P(I,J)_1$

j / i	1	2	3	4	5	6	7	8
1	1	1	1	1	1	1	1	1
2	2	2	1	2	2	2	2	2
3	3	1	3	3	3	3	3	3
4	4	4	4	4	4	4	4	4
5	5	5	5	5	5	5	5	5
6	6	6	6	6	6	6	6	6
7	7	7	7	7	7	7	7	7
8	8	8	8	8	8	8	8	8

This analysis is repeated for K = 2,3,4,5,6,7,8. The final skim tree matrix and back node matrix are as follows.

Table C.5: Skim tree matrix $LT(I,J)_2$

j / i	1	2	3	4	5	6	7	8
1	0	2	4	5	4	7	8	9
2	2	0	4	3	2	7	7	7
3	4	4	0	1	3	3	4	6
4	5	3	1	0	2	4	4	6
5	4	2	3	2	0	6	6	5
6	7	7	3	4	6	0	1	3
7	8	7	4	4	6	1	0	2
8	9	7	6	6	5	3	2	0

Table C.6: Back node matrix $P(I,J)_2$

j / i	1	2	3	4	5	6	7	8
1	-	1	1	2	2	3	6	5
2	2	-	4	2	2	3	4	5
3	3	4	-	3	4	3	6	7
4	2	4	4	-	4	3	4	7
5	2	5	4	5	-	3	4	5
6	3	4	6	3	4	-	6	7
7	3	4	6	7	4	7	-	7
8	2	5	6	7	8	7	8	-

The results are interpreted in the following manner. For origin node i, say (i = 1), to get to node j = 1,2,3,...N, the total travel time is LT(I,J) and the minimum path tree has to go through back node P(1,J). It is in this fashion that the results are printed out.

Table C.7: ORIGIN ZONE 1

TO NODE	TOTAL TRAVEL TIME	BACK NODE
1	0	-
2	2	1
3	4	1
4	5	2
5	4	2
6	7	3
7	8	6
8	9	5

The computer listing is shown on the next page.

This program [MINROUTE] for the route building algorithm is written in Quick Basic. The total number on nodes for the sample network is 8. The computer listing is shown below.

```
10 REM MINIMUM PATH ANALYSIS ALGORITHM
20 DIM L(50, 50), LT(50, 50), P(50, 50)
30 DIM D(50), IN(50), BN(50)
40 READ N
50 FOR I = 1 TO N
60 FOR J = 1 TO N
65 IF J > I GOTO 100
70 READ L(I, J)
75 L(J, I) = L(I, J)
80 LT(I, J) = L(I, J)
85 LT(J, I) = LT(I, J)
90 NEXT J
100 NEXT I
110 FOR I = 1 TO N
111 FOR J = 1 TO N
112 P(I, J) = I
115 NEXT J
116 NEXT I
120 FOR K = 1 TO N
130 FOR I = 1 TO N
140 FOR J = 1 TO N
150 SUM = L(I, K) + L(K, J)
160 IF SUM < L(I, J) THEN L(I, J) = SUM ELSE 180
170 P(I, J) = P(K, J)
180 NEXT J
190 NEXT I
200 NEXT K
210 GOSUB 1000
220 GOSUB 2000
230 END
240 DATA 8
250 DATA 0
260 DATA 2,0
270 DATA 4,999,0
280 DATA 999,3,1,0
290 DATA 999,2,999,2,0
300 DATA 999,999,3,999,999,0
310 DATA 999,999,999,4,999,1,0
320 DATA 999,999,999,999,5,999,2,0
```

```
1000 REM PRINTOUT OF INPUT DATA
1010 LPRINT "LINK TABLE FOR TRAFFIC NETWORK"
1020 LPRINT "------------------------------"
1030 LPRINT : LPRINT
1040 LPRINT "-----------------------------------------------------"
1050 LPRINT "!  NODE FROM  !  NODE TO  !  TRAVEL TIME L(I,J)    !"
1060 LPRINT "-----------------------------------------------------"
1070 FOR I = 1 TO N
1080 FOR J = 1 TO N
1090 IF LT(I, J) = 0 GOTO 1180
1095 IF LT(I, J) = 999 THEN 1180
1100 D(J) = LT(I, J)
1110 VAR1 = I
1120 VAR2 = J
1130 VAR3 = D(J)
1135 LPRINT "!";
1140 LPRINT USING "######"; VAR1;
1145 LPRINT "      !";
1150 LPRINT USING "#######"; VAR2;
1155 LPRINT "    !";
1160 LPRINT USING "###############"; VAR3;
1165 LPRINT "        !"
1170 LPRINT "-----------------------------------------------------"
1180 NEXT J
1190 NEXT I
1200 LPRINT : LPRINT
1210 RETURN

2000 REM PRINTOUT OF RESULTS
2010 LPRINT "MINIMUM PATH TREE RESULTS - TOTAL TRAVEL TIMES AND BACK NODES"
2020 LPRINT "-------------------------------------------------------------"
2030 LPRINT : LPRINT
2040 FOR I = 1 TO N
2050 LPRINT "---------------------------------------------"
2060 LPRINT "       FOR ORIGIN DESTINATION ZONE "; I
2070 LPRINT "---------------------------------------------"
2080 LPRINT : LPRINT
2090 LPRINT "-----------------------------------------------------"
2100 LPRINT "!  TO NODE     !    TOTAL TRAVEL TIME    !   BACK NODE  !"
2110 LPRINT "-----------------------------------------------------"
2120 FOR J = 1 TO N
2130 IN(J) = J: VAR1 = IN(J)
2140 D(J) = L(I, J): VAR2 = D(J)
2150 BN(J) = P(I, J): VAR3 = BN(J)
2155 LPRINT "!";
2160 LPRINT USING "######"; VAR1;
2165 LPRINT "      !";
2170 LPRINT USING "#######.##"; VAR2;
2175 LPRINT "          !";

2180 IF VAR1 = I THEN LPRINT "    -";
2185 IF VAR1 <> I THEN LPRINT USING "######"; VAR3;
2186 LPRINT "      !"
2190 LPRINT "-----------------------------------------------------"
2200 NEXT J
2210 LPRINT : LPRINT
2220 NEXT I
2238 RETURN
```

SECTION II

DISPERSION MODELS

This section of appendix C, contains the dispersion model for LPG. Similar dispersion models have been developed for chlorine and sulphuric acid but, they are not included here for lack of space. Equations, computer listing and output are presented.

DISPERSION MODEL

LIQUEFIED PETROLEUM GAS (LPG)

Relationships Employed in LPG Spill Submodel

Calculate weight in container:

$$W = (V * PF) * D_L$$

$$W_T = W / 1000$$

where: W = weight of LPG in container (kg)
V = container volume (m^3)
PF = percent full (input value)
D_L = density of liquid (kg/m^3)

W_T = weight of LPG in container (tonnes)

Calculate the tonnes spilled:

$$Q_T = SF * W_T$$

where: Q_T = tonnes spilled

SF = fraction of container spilled (input value)

Calculate the amount of flash vapourization:

$$ff = 0.05537 * T + 0.22907$$

where: ff = flashing fraction (Marshall, 1982)
T = temperature (deg C)

Calculate the amount of vapour formed:

$$Q_V = Q_T * (ff + ff * e)$$

where: Q_V = amount of vapour formed instantaneously (tonnes)

e = liquid entrained (input as a fraction of ff)

Relationships for LPG Fireballs

Calculate dimensions:

$$R = C_R * (Q_T)^{1/3}$$

$$A_S = 2 * 3.1416 * R^2$$

$$t_{fb} = C_t * (Q_T)^{1/3}$$

where: R = fireball radius (m)
C_R = coefficient for fireball radius equation

Q_T = quantity spilled (tonnes)

A_S = surface area of fireball (m^2)

t_{fb} = duration of fireball (seconds)

C_t = coefficient for fireball duration equation

Calculate threshold distances:

$$D_{roa} = (E * S * T_{fb} * A_S) / (3.1416 * 1000)$$

$$D_{rob} = (F * H * Q_T * 1000) / (4 * 3.1416 * t_{fb})$$

where: E = gas emissivity
S = Stephan-Boltzman constant ($5.67 * 10^{-8}$ J/sm²K⁴)
T_{fb} = fireball flame temperature (deg K)

F = fraction of heat radiated from fireball
H = heat of combustion (KJ/kg)

Calculate heat flux for a given damage level:

$$H_f = 10 \exp[C_A * \log(t_{fb})/\log 10 + C_B]$$

where: H_f = heat flux (KW/m²)

C_A = coefficient A for a given damage

C_B = coefficient B for a given damage

Calculate distance to damage:

$$D_L = (D_{ros} / H_f)^{1/2}$$

$$D_R = (D_{rob} / H_f)^{1/2}$$

where: D_L = Rose's distance to a given damage level (m)

D_R = Robert's distance to a given damage level (m)

Relationships for LPG Vapour Cloud Explosions

Calculate TNT equivalent weight:

$$W = (E * H_{cp} * Q_v * 1000) / H_{cTNT}$$

where: W = TNT equivalent weight (kg)

E = constant

H_{cp} = propane heat of combustion (cal/kg)

Q_v = quantity of propane vapour (tonnes)

H_{cTNT} = TNT heat of combustion (cal/kg)

Calculate distance to damage:

$$L = C * W^{1/3}$$

where: L = distance to damage (m)

C = coefficient for specific damage level

Relationships for LPG in the pool:

Calculate amount of LPG in the pool:

$$W = Q_T - Q_V$$

where: W = quantity LPG in pool (tonnes)
Q_T = total quantity spilled (tonnes)

Q_V = quantity of vapour formed (tonnes)

Calculate pool volume and area:

$$V = (W * 1000) / D_L$$

$$A = V / (d * 0.01)$$

where: V = volume (m^3)
D_L = liquid density (kg/m^3)

A = area (m^2)
d = pool depth (cm)

Calculate energy radiating to surroundings:

$$Q = R_B * R_{HR}$$

where: Q = rate of radiation per unit area (KJ/m^2s)
R_B = burning rate (kg/m^2s)

R_{HR} = heat release rate (KJ/kg)

Calculate the distance to damage:

$$X = (Q / (4 * 3.14 * H_f))^{1/2} * A^{1/2}$$

where: X = distance to a specific damage (m)
H_f = heat flux to produce the damage (KW/m^2)

SPILL CHARACTERISTICS

```
CONTAIN:  volume:   13.50 m^3        filled 0.85
liquid :  density: 493.50 kg/m^3    weight: 5.66 tonnes
SPILL  :  fraction:  1.00           weight: 5.66 tonnes

AIR CON:  temp deg cel. : 20 C                     stability: D
VAPOUR :  flash-off %   : 33.98   liq. entrain % of flash-off: 100
```

FIREBALL FORMATION

```
COEFFICI:  radius:   27.5          duration:  3.76
FIREBALL:  radius:   49.0 m     surface :  15096.4 m^2
DURATION:  time:      6.7 secs
DISTANCE:  638257 m
```

```
HAZARD: Blistering of Bare Skin
HEAT FLUX: 13.58 kw/m^2   COEFFICIENTS: a: -0.748   b: 1.75
DISTANCE:  216.8 m              AREA:   0.15 km^2

HAZARD: Ignition of Cellulose Material
HEAT FLUX: 53.40 kw/m^2   COEFFICIENTS: a: -0.412   b: 2.07
DISTANCE:  109.3 m              AREA:   0.04 km^2

HAZARD: 1% Mortality
HEAT FLUX: 44.99 kw/m^2   COEFFICIENTS: a: -0.742   b: 2.27
DISTANCE:  119.1 m              AREA:   0.04 km^2

HAZARD: 50% Mortality
HEAT FLUX: 79.53 kw/m^2   COEFFICIENTS: a: -0.750   b: 2.52
DISTANCE:  89.6 m               AREA:   0.03 km^2
```

VAPOUR CLOUD SHOCK WAVE

```
HEAT CONTENT PROPANE: 1.196E+07 (CAL/KG)   HEAT CONTENT TNT:   1.106E+06 (CAL/KG)
 EFFICIENCY FACTOR E: 0.10           TNT EQUIVALENT WEIGHT:   4.16 tonnes
```

```
HAZARD:  None
DAMAGE:  type:  1    COEFFICI:    150   DISTANCE:  2412.8 m   AREA:  18.280 km^2

HAZARD:  Injury to people; Window Breakage
DAMAGE:  type:  2    COEFFICI:     10   DISTANCE:   160.9 m   AREA:   0.081 km^2

HAZARD:  Wooden Doors Damaged
DAMAGE:  type:  3    COEFFICI:      7   DISTANCE:   112.6 m   AREA:   0.040 km^2

HAZARD:  Damage to Light Partitions
```

```
DAMAGE:  type: 4    COEFFICI:      5  DISTANCE:    72.4 m   AREA:   0.016 km^2

HAZARD:  Damage to Brick Walls
DAMAGE:  type: 5    COEFFICI:      4  DISTANCE:    56.3 m   AREA:   0.010 km^2

HAZARD:  Destruction of Masonary Buildings
DAMAGE:  type: 6    COEFFICI:      2  DISTANCE:    24.1 m   AREA:   0.002 km^2

------------------------------------------------------------------------
```

POOL FIRE

```
POOL:      thickness :  2.0 cm                        area:  183.82 m^2
PROPANE:  burning rate: 0.13 kg/m^2 s    heat release rate: 50359 kJ/kg
------------------------------------------------------------------------
HAZARD: Blistering of Bare Skin
DAMAGE: type:  1      thermal intensity:  6.0 km/m^2
DISTANCE:  126 m      HAZARD AREA:      0.050 km^2

HAZARD: Ignition of Cellulose Material
DAMAGE: type:  2      thermal intensity: 34.0 kw/m^2
DISTANCE:   53 m      HAZARD AREA:      0.009 km^2

HAZARD:  1% Mortality
DAMAGE:  type:  3     thermal intensity: 20.0 kw/m^2
DISTANCE:    69 m     HAZARD AREA:      0.015 km^2

HAZARD:  50% Mortality
DAMAGE:  type:  4     thermal intensity: 35.0 kw/m^2
DISTANCE:    52 m     HAZARD AREA:      0.009 km^2
```

```
200    GOSUB 2000 ' read    spill characteristics data
250    GOSUB 3000 ' calculate spill characteristics
251      IF (INKEY$ = "")  GOTO 251    ' screen hold
300    GOSUB 4000 ' compute fireball characteristics
351      IF (INKEY$ ="")   GOTO 351    ' screen hold
400    GOSUB 5000 ' compute shockwave impacts
451      IF (INKEY$= "")   GOTO 451    ' screen hold
500    GOSUB 7000 ' compute pool fire impacts
899  PRINT "done
900  END
999 '-----------------------------------------------------------
2000 '----------------------------------------------------------
2010  '  generation of spill
2100         GOSUB 2400   ' read spill characteristics
2200         GOSUB 2500   ' read fireball related characteristics
2210         GOSUB 2600   ' read shock wave related characteristics
2220         GOSUB 2700   ' read pool fire related characteristics
2290     RETURN
2400 '  --------
2410 '         spill characteristics
2420 '
2430            READ CONVOL          ' nominal volume of container  (m^3)
2440            READ CONFUL          ' fraction of filling of container
2450            READ CONDEN          ' density of liquid in container  (kg/m^3)
2455 '
2460            READ SPLFRA          ' fraction of container spilled
2480            READ IGNDEL          ' delay of ignition following (minutes)
2481            READ SPLTEM          ' temperature  (deg C)
2482            READ SPLENT          ' entrained liquid as a fraction of the flashing fraction
2485 '
2490      RETURN
2500 ' ---------
2510 '        fireball  characteristics
2520 '
2530        READ BALRDC , BALDUC       ' fireball radius and duration coefficients
2540 '
2550       READ BALE, BALSB, BALTEM   ' fireball gas emmissivity, Stephan-Boltzman const, flame temp
                                         (deg k)
2555        READ BALF, BALHEAT         ' fireball fraction of heat release, combustion heat (kJ/kg)
2560 '
2565     FOR DAM = 1 TO 4
2570          READ BALFLA(DAM), BALFLB(DAM)  'damage parameters for damage type dam
2585     NEXT DAM
2590   RETURN
2600 '--------
2610 '        shock wave characteristics data
```

```
2620 '
2630        READ VAPE            ' efficiency factor in TNT calculation
2640        READ VAPHCP          ' heat content of propane
2645        READ HCTNT           ' heat content of TNT
2650'
2660    FOR DAM = 1 TO 6
2670         READ VAPC(DAM)      ' damage coefficients for blast wave damage
2680    NEXT DAM
2690  RETURN
2700 '--------
2710 '      pool fire impact data
2720 '
2730         READ POLTHK         ' liquid pool thickness (cm)
2740         READ POLBR          ' propane burning rate (kg/m^2 s)
2750         READ POLHRR         ' propane heat release rate (kJ/kg)
2760 '
2770     FOR DAM = 1 TO 4
2780         READ POLTI(DAM)     ' thermal intensity levels causing damage
2785     NEXT DAM
2790  RETURN
3000 PRINT "-------------------------------------------------------
3020 PRINT "   SPILL CHARACTERISTICS     "
3030 PRINT
3100    CONWKG = (CONVOL * CONFUL) * CONDEN   ' weight of lpg in container (kg)
3110    CONWTO = CONWKG / 1000                ' weight of lpg in container (tonne)
3120 '
3200    SPLTON = SPLFRA * CONWTO                         ' spill tonnage
3210    SPLFLA = (.005537 * SPLTEM) + .22907             ' Marshall's flashing fraction
3220    SPLVAP = SPLTON * ( SPLFLA + SPLFLA *SPLENT )  ' instantaneous vapour formation (tonnes)
3400 '
3500    PRINT USING "CONTAIN:  volume:   ##.## m^3       filled #.##  "; CONVOL , CONFUL
3510    PRINT USING "liquid :  density: ###.## kg/m^3   weight: ##.## tonnes" ; CONDEN,CONWTO
3520    PRINT USING "SPILL  :  fraction:  #.##          weight: ##.## tonnes" ; SPLFRA, SPLTON
3560    PRINT
3600    PRINT USING "AIR CON:  temp deg cel. :### C                 stability: D " ; SPLTEM
3610   PRINT USING "VAPOUR:flash-off %:##.## liq. entrain % of flash-off:###"; SPLFLA*100, SPLENT*100
3700    PRINT
3710  '
3900   RETURN
4000 '-------------------------------------------------------
4005  PRINT "-------------------------------------------------------
4010  PRINT "    FIREBALL FORMATION        "
4050      BALRAD = BALRDC * ( SPLTON ^ ( 1/3) )    ' fireball radius (metres)
4055      BALSUR = 2 * 3.1416 * (BALRAD ^ 2    )    ' fireball surface area (m^2)
4070      BALDUR = BALDUC * ( SPLTON ^ (1/3)  )    ' fireball duration (secs)
4100 '
4110      BALROS = BALE * BALSB * ( BALTEM ^ 4 ) * BALSUR / (3.1416 *1000) 'rose threshold distance
4120      BALROB = BALF * BALHEAT * SPLTON * 1000 / ( 4 * 3.1416 * BALDUR ) 'robert's thresh. dist.
4130 '
4140      PRINT USING "COEFFICI:  radius: ####.#        duration: ##.##    " ; BALRDC, BALDUC
4150      PRINT USING "FIREBALL:  radius: ####.# m   surface: ######.# m^2" ; BALRAD, BALSUR
4160      PRINT USING "DURATION:  time:    ####.# secs                     " ; BALDUR
```

```
4170        PRINT USING "DISTANCE:  ####### m                              " ; BALROS
4175        PRINT "----------------------------------------------------------
4200 '
4205     FOR DAM = 1 TO 4
4210       BALFLU(DAM) = 10^(BALFLA(DAM)*LOG(BALDUR)/LOG(10)+BALFLB(DAM)) 'heat flux from damage dam
                                                                            (kw / m^2)
4220       BALDIL(DAM) = (BALROS / BALFLU(DAM)) ^ .5      ' threshold distance to damage (m) - Rose
4225       BALDAR = 3.14 * (BALDIL(DAM) * .001) ^ 2       ' area of damage (km) -Rose
4230       BALDIH(DAM) = (BALROB / BALFLU(DAM)) ^ .5     ' threshold distance to damage (m) - Roberts
4240       BALDAT = 3.13 * (BALDIH(DAM) * .001)^2         ' area of damage (km) - Roberts
4600 '
4610  IF DAM = 1, GOTO 4650
4620  IF DAM = 2, GOTO 4660
4630  IF DAM = 3, GOTO 4670
4640  IF DAM = 4, GOTO 4680
4650  PRINT "HAZARD:  Blistering of Bare Skin
4655  GOTO 4700
4660  PRINT "HAZARD:  Ignition of Cellulose Material
4665  GOTO 4700
4670  PRINT "HAZARD:  1% Mortality
4675  GOTO 4700
4680  PRINT "HAZARD:  50% Mortality
4700   PRINT USING "HEAT FLUX:###.##kw/m^2 COEFFICIENTS:a:####.###
                    b:###.##";BALFLU(DAM),BALFLA(DAM),BALFLB(DAM)
4810   PRINT USING "DISTANCE: ####.# m             AREA: ###.## km^2   "; BALDIL(DAM), BALDAR
4850   PRINT
4880 NEXT DAM
4900   RETURN
5000 '-------------------------------------------------------------
5005  PRINT "----------------------------------------------------------
5007  PRINT
5010  PRINT " VAPOUR CLOUD SHOCK WAVE  "
5030        VAPTNT = (VAPE * VAPHCP * SPLVAP * 1000) / HCTNT   ' calculate TNT equivalent weight (kg)
5035        VAPTNTT = VAPTNT / 1000                              ' TNT equivalent weight (tonnes)
5040 '
5050         PRINT USING "HEAT CONTENT PROPANE:##.###(CAL/KG)  HEAT CONTENT TNT: ##.### (CAL/KG)
                                               ";VAPHCP,HCTNT
5060         PRINT USING " EFFICIENCY FACTOR E: #.##        TNT EQUIVALENT WEIGHT: #####.## tonnes ";
                                               VAPE,VAPTNTT
5065         PRINT  "--------------------------------------------------------------"
5070 '
5080 FOR DAM = 1 TO 6
5090     VAPL(DAM) = VAPC(DAM) * ( VAPTNT ^(1/3) )            ' calculate the distance to damage (m)
5095      VAPARE = 3.14 * (VAPL(DAM) * .001) ^ 2                ' calculate hazard area (km)
5100 '
5110  IF DAM = 1 GOTO 5180
5120  IF DAM = 2 GOTO 5200
5130  IF DAM = 3 GOTO 5220
5140  IF DAM = 4 GOTO 5240
5150  IF DAM = 5 GOTO 5260
5160  IF DAM = 6 GOTO 5280
5180  PRINT "HAZARD:  None
```

```
5190  GOTO 5300
5200  PRINT "HAZARD:  Ijury to People; Window Breakage
5210  GOTO 5300
5220  PRINT "HAZARD:  Wooden Doors Damaged
5230  GOTO 5300
5240  PRINT "HAZARD:  Damage to Light Partitions
5250  GOTO 5300
5260  PRINT "HAZARD:  Collapse of Brick Walls
5270  GOTO 5300
5280  PRINT "HAZARD:  Destruction of Masonary Buildings
5300      PRINT USING "DAMAGE:  type: ##       ";DAM   ;
5400      PRINT USING "COEFFICI:      ###       ";VAPC(DAM)
5500      PRINT USING "DISTANCE:  ####.# m    AREA: ###.### km^2 ";VAPL(DAM),VAPARE
5600      PRINT
5700  NEXT DAM
5950 RETURN
7000 '----------------------------------------------------------------------
7005  PRINT "-----------------------------------------------------
7007  PRINT
7010  PRINT "     POOL FIRE          "
7016      POLWIT = SPLTON - SPLVAP              ' calculate weihgt of propane in pool (tonnes)
7017      POLVOL = (POLWIT * 1000) / CONDEN     ' calculate pool volume (m^2)
7020      POLAREA = POLVOL / (POLTHK * .01)     ' calculate area of the pool (m^2)
7030      POLQ = POLBR * POLHRR      ' calcuate rate of energy radiation to surroundings per area
                                      (kJ/m^2 s)
7040 '
7050      PRINT USING "POOL:     thickness : ###.# cm       area: ####.## m^2"; POLTHK,POLAREA
7055      PRINT USING "PROPANE:  burning rate: #.## kg/m^2 s   heat release rate: ##### kJ/kg";
                                                    POLBR,POLHRR
7060      PRINT "-----------------------------------------------------
7070 '
7080  FOR DAM = 1 TO 4
7090 POLX(DAM)=((POLQ/(4*3.14*POLTI(DAM)))^(1/2))*((POLAREA)^(1/2)) 'distance to damage using inverse
                                                                      sq law
7095  POLARE = 3.14 * (POLX(DAM) * .001) ^ 2     'calculate hazard area (km)
7100 '
7110  IF DAM = 1, GOTO 7150
7120  IF DAM = 2, GOTO 7160
7130  IF DAM = 3, GOTO 7170
7140  IF DAM = 4, GOTO 7180
7150  PRINT "HAZARD:  Blistering of Bare Skin
7155  GOTO 7200
7160  PRINT "HAZARD:  Ignition of Cellulose Material
7165  GOTO 7200
7170  PRINT "HAZARD:  1% Mortality
7175  GOTO 7200
7180  PRINT "HAZARD:  50% Mortality
7200      PRINT USING "DAMAGE:  type: ##      thermal intensity: ##.# kw/m^2     "; DAM, POLTI(DAM)
7300      PRINT USING "DISTANCE: ##### m      HAZARD AREA:  ###.### km^2"; POLX(DAM), POLARE
7350      PRINT
7400    NEXT DAM
7900     '
```

```
7910        RETURN
10000 '-----------------------------------------------------------------------
20000 ' input data for model
21000     DATA    13.5      : ' nominal container volume  (m^3)
21100     DATA     .85      : ' fraction of container filled  (fraction filled)
21200 '
21300     DATA   493.5      : ' density of liquid in container (kg/m^3) -- CRC Handbook
21400 '
21500     DATA     1.0      : ' fraction of container spilled
21600 '
21700     DATA      .1      : ' delay of ignition ( minutes )
21800     DATA     20       : ' temperature (degree celcius)
21900     DATA      1       : ' entrained liquid as a percent of flashing fraction
21999 '
22000 ' fireball data
22100     DATA  27.5  , 3.76          :' fireball radius and duration coefficients
22200     DATA  .1  , 5.67E-08, 2200  :' gas emmissivity, Stephan-Boltzman const, flame temp (deg k)
22300     DATA 0.3  , 50340           :' fraction of heat release--Roberts, heat of combustion (kJ/kg)
22350 '
22400     DATA -.7481, 1.751          :' coefficients a and b for blistering bare skin -- Roberts,
1982
22420     DATA -.4121, 2.068          :' coefficients a and b for ignition of cellulose material
22430     DATA -.7418, 2.266          :' coefficients a and b for 1% mortality rate
22440     DATA -.7498, 2.52           :' coefficients a and b for 50% mortality rate
22999 '
23000 ' shockwave  data
23100     DATA    .1                  :' efficiency factor
23110     DATA   1.196E07             :' heat content propane  (cal/kg) -- Rose (1984)
23120     DATA   1.106E06             :' heat content TNT      (cal/kg) -- Rose
23125 '
23130     DATA   150                  :' C coefficient for no damage (range 50-150) -- Clency (1982)
23140     DATA   10                   :' C coefficient for injury to people, glass windows broken
23150     DATA   7                    :' C coefficient for damage to wooden doors
23160     DATA   4.5                  :' C coefficient for destruction of light partitions
23170     DATA   3.5                  :' C coefficient for collapse of brick walls in small buildings
23180     DATA   1.5                  :' C coefficient for destruction of stone and brick buildings
23999 '
24000  ' pool fire data
24100     DATA    2                   :' pool thickness (cm)
24200     DATA    .13                 :' propane burning rate (kg/m^2) -- Mizner and Eyre (1982)
24300     DATA    50359               :' propane heat release rate (kJ/kg) -- CRC Handbook
24400     DATA    6                   :' blistering of bare skin in 20 seconds (kw/m^2) -- Roberts
24500     DATA   34                   :' ignition of cellulose materials (kw/m^2)
24600     DATA   20                   :' 1 % mortality rate              (kw/m^2)
24700     DATA   35                   :' 50 % motality rate              (kw/m^2)
```

APPENDIX - D

TABLES & SAMPLE CALCULATIONS

Tables obtained from literature review that were useful in this study are listed in this Appendix. Sample risk calculations for the various hazardous materials is also attached.

The tables listed include:

1. D.1 Hazard areas and fatalities for different release profiles on road [11].
2. D.2 Default truck accident rates and release probabilities for use in hazardous materials routing and analysis [8].
3. D.3 Additional data.

- Sample calculations.
- Classification of HM in Canada

Table D.1 **Hazard Areas and Fatalities for Different Release Profiles on Road [13].**

Material	Type of Release	Hazard Area (Km^2) 50% Fatality (800 PPM)	1% Fatality (300 PPM)	Fatalities** per density
Chlorine				
	Instantaneous			
	High	1.072	1.112	0.0870
	Medium	0.855	1.059	0.0745
	Low	0.804	0.832	0.0652
	Continuous			
	High	0.650	1.160	0.0673
	Medium	0.043	0.078	0.0045
	Low	0.001	0.002	0.0001
LPG				
	Instantaneous			
	High	0.070	0.130	0.0021
	Medium	0.070	0.120	0.0021
	Low	0.050	0.090	0.0015

** Population density per 1 pers.per sq. Km.
Assumed wind speed 5km/H.
Atmospheric stability condition D.

Table D.2 **Default Truck Accident Rates and Release Probability for Use in Hazardous Materials Routing and Analysis [8].**

Area type	Roadway type	Truck acc. rate (acc. per 10^6 veh-mi)	Probability of release given an accident	Releasing acc. rate (release per 10^6 veh-mi)
Rural	Two-lane	2.19	0.086	0.19
Rural	Multilane undivided	4.49	0.081	0.36
Rural	Multilane divided	2.15	0.082	0.18
Rural	Freeway	0.64	0.092	0.60
Urban	Two-lane	8.66	0.069	0.60
Urban	Multilane undivided	13.92	0.055	0.77
Urban	Multilane divided	12.47	0.062	0.77
Urban	One-way street	9.70	0.056	0.54
Urban	Freeway	2.18	0.062	0.14

Table D.3 **Additional Data**

Area type	Roadway type	Releasing acc. rate per 10^6 veh-mi	Releasing acc. rate per 10^6 veh-km	% truck
Rural	Two-lane	0.19	0.235	10
Rural	Multilane undivided	0.36	0.124	12
Rural	Multilane divided	0.18	0.118	15
Rural	Freeway	0.06	0.039	20

Sample Risk Calculations

Road segment

AADT = 3500 vehicles

Population density = 300 pers/km^2

Distance = 10 km

Area type = Rural

Roadway type = Multilane divided

From Table D.2:

Releasing accident rate = .18 per million veh-mi

= .118 per million veh-km

From Table D.3: Percentage of trucks on roadway = 15%

Average daily trucks = 0.15 * 3500

= 525 trucks

Vehicle-km on link = 525trucks * 10km * 365

= 1,916,250 veh-km

Accident probability = $(1,916,250 * 0.118)/10^6$

= 0.230

LPG

From dispersion model in Appendix C and, also from table D.1,

Hazard area = $0.05km^2$

Fatalities per density exposed = 0.0015

Fatalities per density of $300pers/km^2$ = 300 * 0.0015

= 0.45

Risk = (Accident probability) * (Accident consequences)

Risk(population) = 0.230 * 0.45

= 0.1035 fatalities

Assuming a penetration depth of 1m,

Volume of soil contaminated = $0.05m^3$

Risk(environment) = 0.230 * 0.05

= $0.0115m^3$ contaminated soil.

Chlorine Gas

From Table D.1,

Hazard area = $1.072km^2$

Fatalities per density exposed = 0.0870

Fatalities per density of $300pers/km^2$ = 300 * 0.0870

= 26.1

Risk(population) = 0.230 * 26.1

= 6 fatalities

Risk to soil for chlorine is negligible.

Sulphuric Acid

Risk to population is negligible since it does not release toxic fumes due to its high boiling point.

From dispersion model for sulphuric acid in Appendix C, volume of soil contaminated = 0.05 km^3.

Risk(environment) = 0.230 * 0.05

= 0.0115 km^3 soil contaminated.

CLASSIFICATION OF HAZARDOUS MATERIALS IN CANADA

The Transportation of Dangerous Goods Act (TDGA) divides dangerous goods into nine classes, according to the type of danger they present [19]. Some of these classes are further divided into divisions which are also associated with hazard characteristics.

The nine classes are:

Class 1: Explosives

- 1.1 Capable of producing a mass explosion.
- 1.2 A projection hazard but not a mass explosion hazard.
- 1.3 A fire hazard with minor projection and/or minor blast.
- 1.4 A minor hazard, effects confined largely to package.
- 1.5 Insensitive explosive substances.

Class 2: Gases

- 2.1 Inflammable gases.
- 2.2 Gases not poisonous or flammable.
- 2.3 Poisonous gases.
- 2.4 Corrosive gases.

Class 3: Flammable and Combustible Liquids

- 3.1 Having flashpoint below -18 degree celsius.
- 3.2 Having flashpoint -18 to 37.8 degree celsius.
- 3.3 Having flashpoint 37.8 to 93.3 degree celsius.

Class 4: Flammable Solids

- 4.1 Combustible through friction or heat retained from processing.

4.2 Liable to spontaneous heating in contact with air.

4.3 Emit flammable gases or spontaneously combustible with water or water vapour.

Class 5: Oxidizing Substances and Organic Substances

5.1 Oxidizing substances which increase risk or intensity of fire.

5.2 Organic peroxides either combustible or oxidizers.

Class 6: Poisonous (toxic) and Infectious Substances

6.1 Poisonous by inhalation, ingestion, skin contact.

6.2 Infectious substance.

Class 7: Radioactive Materials and Prescribed Substances within the Atomic Energy Control Act.

Class 8: Corrosives causing severe damage to living tissue or freight by means of transport.

Class 9: Miscellaneous Products or Substances

9.1 Miscellaneous dangerous goods.

9.2 Environmental hazardous substances.

9.3 Dangerous waste products.