RISKS OF TRANSPORTING DANGEROUS GOODS: SOUTH DURBAN CASE STUDY

by

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ABSTRACT

Industry both consumes and creates an abundance of dangerous goods, which must be transported from producers to end-users. This creates opportunities for incidents, including traffic accidents, which could release poisonous, corrosive, flammable or carcinogenic substances into the environment. Releases of dangerous goods at a location may pose a significant threat to the health of the neighbouring population. The Durban South Basin, with its hazardous mix of heavy industrial, employment and residential areas, was chosen as the case study for research into the risks associated with the transportation of dangerous goods. High levels of traffic flow occur in this region and significant volumes of dangerous goods are transported on the roads within the basin. The objectives of this investigation were to: develop a methodology that may be applied to estimate the likelihood and consequences of releases of dangerous goods due to road accidents; and to evaluate the usefulness of this methodology by applying it to estimate the risks posed to the people residing in, working in and travelling through the Durban South Basin.

The literature pertaining to risk assessment of dangerous goods transport was examined. A review was undertaken of the current state of the art and the theory and methodology used by previous researchers. As intersections provide greater opportunities for vehicles to be involved in accidents, traffic surveys were conducted at selected intersections within the Durban South Basin in order to obtain an indication of the flow of dangerous goods vehicles and the types of dangerous goods being transported through these locations. Two approaches were utilised to estimate the likelihood of dangerous goods accidents and releases at intersections: a deterministic model and an innovative method based on Monte Carlo simulation. Dispersion modelling and geographic information systems were integrated to estimate the impacts of accidental releases of dangerous goods at intersections. Queuing analysis was combined with dispersion modelling to estimate the risks posed to road users from dangerous goods releases. The investigation verified that dangerous goods transportation risk assessment could be performed even when there are substantial data uncertainties. Furthermore, in comparison to the deterministic approach typically used in transportation studies, Monte Carlo simulation facilitates a deeper understanding of the nature and distribution of dangerous goods accident risk. The results suggest that although dangerous goods accidents and releases are infrequent, the potential exists for very serious incidents involving large numbers of injuries.

PREFACE

Unless specifically indicated to the contrary in the text, this whole dissertation is the work of Bhavesh Raman Govan and has not been submitted in part, or in whole to any other University.

The work described in this dissertation was carried out at the School of Civil Engineering, Surveying and Construction at the University of KwaZulu-Natal, Durban, under the supervision of Professors DD Stretch and CS Roebuck.

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LIST OF SYMBOLS

The following is a list of the symbols (including units of measure) used in this document.

°C	degree(s) Celsius
hr	hour(s)
kg	kilogram(s)
km	kilometre(s)
km^2	square kilometre(s)
m	metre(s)
m^2	square metre(s)
m^3	cubic metre(s)
min	minute(s)
s	second(s)
T	temperature
veh	vehicles
yr	year(s)
α	level of significance
χ^2	Chi-squared

LIST OF ABBREVIATIONS

The following is a list of the acronyms and abbreviations used in this document.

AADT	Annual average daily traffic volume
ACN	Acrylonitrile
ADMS™	Advanced Dispersion Modelling System
CAIA	Chemical and Allied Industries' Association
CASRAM	Chemical Accident Statistical Risk Assessment Model
CERC	Cambridge Environmental Research Centre
CSIR	Council for Scientific and Industrial Research
DALR	Dry Adiabatic Lapse Rate
DEGADIS	Dense Gas Dispersion Model
ELR	Environmental Lapse Rate
ERPG	Emergency Response Planning Guideline
FHWA	Federal Highway Administration
GIS	Geographical Information Systems
HF	Anhydrous Hydrogen Fluoride
HMIS	Hazardous Materials Information System
IDLH	Immediately Dangerous to Life or Health concentration
ITS	Intelligent Transportation Systems
KS	Kolmogorov-Smirnov
LDV	Light delivery vehicle
L_{MO}	Monin-Obukhov length
ln	natural logarithm
LPG	Liquefied Petroleum Gas
MEC	Member of the Executive Council of a province
MHI	Major Hazard Installation
NIOSH	National Institute for Occupational Safety and Health
NIWAR	National Institute of Water and Atmospheric Research
O-D	Origin-destination
ppb	parts per billion
ppm	parts per million
PRNG	Pseudo-random number generator
RSPA	Research and Special Programs Administration
SANS	South African National Standard

SAPREF	South African Petroleum Refineries
SDCEA	South Durban Community Environmental Alliance
TIH	Toxic-by-inhalation
UK	United Kingdom
UN	United Nations
UNEP	United Nations Environment Programme
U.S.	United States of America
USDOT	United States Department of Transportation
US-EPA	United States Environmental Protection Agency

CHAPTER 1

1. INTRODUCTION

1.1 Background

Along with the advances taking place in our society comes an increasing potential for danger. Many conveniences taken for granted in modern civilization depend in part on dangerous goods. Industry both consumes and creates an abundance of dangerous goods that must be stored, transported and handled. Dangerous goods are substances, which by virtue of their chemical, physical or toxicological properties, pose a significant risk to health, safety, property or the environment [Lepofsky, Abkowitz, & Cheng, 1993]. Dangerous goods include explosives, gases, flammable liquids and solids, oxidizing substances, poisonous and infectious substances, corrosive substances and hazardous wastes. As these products are needed for industries and consumers, the question of banning them is impractical in most cases.

These materials must be transported from producers to end users, which creates opportunities for incidents that could release dangerous goods into the environment. An incident is defined as any unintentional release of dangerous goods during the transport process, including loading and unloading. Vehicular accidents form a subset of incidents. The public is becoming much more aware of and concerned with the hazards associated with the transportation of dangerous goods. This increased awareness has lead to the introduction of regulatory policies and legislation aimed at reducing the risks of these shipments, e.g. the National Road Traffic Act [1996].

1.2 Motivation for this study

Domestic flows of dangerous goods are significant and growing. Over three hundred million tonnes of chemicals were transported by road, rail and pipeline in South Africa in 2002. During this period there were approximately two hundred transportation incidents involving the unintentional release of chemicals [CAIA, 2003]. At present, the selection of transport routes for the carriage of dangerous goods by road is solely based on commercial considerations. The availability of en-route facilities for managing emergencies is not taken into account. Other factors like avoiding population centres, tunnels, etc. when there are alternatives, are generally not considered when selecting a particular route.

The Durban South Basin contains heavy industry such as the Engen and SAPREF oil refineries and Island View Storage, the largest chemical storage facility in the southern hemisphere [CSIR, 1999]. Intertwined with these facilities are the residential areas of Bluff, Clairwood, Isipingo, Merebank, Umlazi and Wentworth. These heavy industries generate an important but dangerous flow of goods that results in road tankers carrying dangerous goods travelling very close to, or through these residential areas. These high flows of dangerous goods, when combined with South Africa's poor road safety record, create numerous opportunities for incidents that could release dangerous goods into the environment. Internationally, traffic accidents are the leading cause of severe dangerous goods incidents (i.e. deaths, injuries, etc) [Harwood & Russell, 1989]. To reduce the chances of a catastrophe occurring as a result of a dangerous goods release within the facility, Engen, SAPREF and Island View Storage are equipped with water deluge systems, containment, foam generation systems and fire proofing, along with scheduled inspection and maintenance. The same high levels of protection are not found on road tankers that transport dangerous goods.

It is a legal requirement that a risk assessment must be performed for all Major Hazard Installations, i.e. installations, which store or handle dangerous goods in quantities sufficient to pose a hazard to the public in the event of a catastrophic on-site incident [Occupational Health and Safety Act, 1993]. Yet, many dangerous goods are transported on the road network in quantities sufficient to result in significant public health impacts if released en-route. Hence, there is a need to perform risk assessments for dangerous goods transport. The *Durban South Basin Strategic Environmental Assessment* [CSIR, 1999] has recommended that the future development of the area should be industrial. There is likely to be further industrial expansion and increased traffic of goods vehicles within the basin. Hence, an assessment of the impacts of transport-related releases of dangerous goods is even more relevant.

1.3 Objectives

Taking into consideration the situation outlined in Sections 1.1 and 1.2, the objectives of this investigation are as follows:

To develop a methodology that may be applied to estimate the likelihood and consequences of releases of dangerous goods due to road accidents.

To evaluate this methodology by applying it to estimate the risks posed to the people residing in, working in and travelling through the Durban South Basin.

1.4 Approach

To fulfil the objectives of this investigation, the following approach was adopted:

The literature pertaining to risk assessment of dangerous goods transport was examined. The current state of the art and the theory and methodology used in previous risk analyses were identified. Intersections provide greater opportunities for dangerous goods carrying vehicles to be involved in accidents. Hence, traffic surveys were conducted at selected intersections within the Durban South Basin in order to obtain an indication of the flow of dangerous goods vehicles and the types of dangerous goods being transported through these locations.

Two approaches were developed to estimate the likelihood of dangerous goods accidents and releases at intersections: a deterministic model and an innovative method based on Monte Carlo simulation. Toxic materials of interest to this investigation are those that could give rise to dispersing vapour clouds upon release into the atmosphere. Dispersion modelling in combination with geographic information systems was used to estimate the impacts of dangerous goods releases at the selected intersections. These results were also integrated with queuing analysis to estimate the risks to road users.

1.5 Overview of chapters

The structure of this dissertation is as follows:

Chapter 2: summarises the main issues associated with the transportation of dangerous goods. The concept of risk is defined. Tools and techniques that may be applied to fulfil the objectives of this investigation are identified. Noteworthy incidents during the transportation of dangerous goods are reviewed. Local legislation pertaining to dangerous goods transport is summarised.

Chapter 3: describes the selection of the case study for this investigation. Hazard identification, the first step in the process of risk analysis, is outlined. The outcomes of the traffic surveys conducted at selected intersections within the Durban South Basin, are presented.

Chapter 4: describes the methodology developed to estimate dangerous goods accident and release rates at intersections.

Chapter 5: describes the methodology utilised to estimate the consequences of dangerous goods releases at intersections.

Chapter 6: concludes this dissertation, summarising the work that has been carried out and the findings of this investigation. Directions on further research are indicated.

CHAPTER 2

2. LITERATURE REVIEW

This chapter summarises the main issues associated with the transportation of dangerous goods. The literature pertaining to risk assessment of dangerous goods transport is examined. An account is given of the theory and methodology used by previous researchers as well as of the current state of the art. This review is not meant to be exhaustive. Further review of the literature and many additional references may be found in the papers cited in this chapter.

2.1 Critical Issues in the Transport of Dangerous Goods

2.1.1 Overview of dangerous goods transportation risk

Most dangerous goods are not used at their point of production and they may be transported over considerable distances. What differentiates shipments of dangerous goods from shipments of other materials, is the risk associated with the accidental release of these materials during transportation. Dangerous goods are extremely harmful to human health, since exposure to the toxic chemical constituents may lead to injury or death. Although accident probabilities are quite low for any given trip, the sheer amount of dangerous goods shipments means that there will be some accidents over a sufficiently long period of time [Erkut & Verter, 1998].

While public safety is the primary concern in dangerous goods incidents, environmental damage may have severe short and long-term effects. Drainage structures are highway components and releases onto a road surface may be quickly carried away to storm water or natural drainage channels. This may impair the emergency responders' ability to mitigate and clean up a release and may be extremely important in areas where streams, lakes, habitats, wildlife reserves or other ecologically sensitive areas are adjacent to the roadway. For example, a dangerous goods spill that reaches a river may harm the birds, fish and other animals that frequent the river and its banks [FHWA, 1994].

Fortunately, it is possible to reduce the risks associated with the transport of dangerous goods. Proper driver training, enhanced vehicle maintenance, improved tank design and careful emergency-response planning all contribute to the reduction of transport-related risks. This risk is recognized by society and in many countries, strict regulations govern the movement of dangerous goods. As a result, dangerous goods carriers often have better accident records than other carriers [Erkut & Verter, 1998]. Nevertheless, even though they are a rare occurrence, accidents do happen during the transportation of dangerous goods. In a particularly noteworthy accident in Afghanistan in 1982, 2 700 fatalities were reported due to a fuel tanker explosion inside a tunnel. The annual number of fatalities due to regular traffic accidents is much greater than the average annual number of fatalities due to dangerous goods transportation accidents. However, dangerous goods transportation accidents receive special attention by the media, which sensitises the public to the hazard of transporting dangerous goods [Erkut & Verter, 1998].

2.1.2 Interested and affected parties

There are several different stakeholders that have an interest in the reduction of dangerous goods transportation risk, both to the population and to the environment. These include:

- The general public who are exposed to the risks from the shipments, and who are becoming more concerned with environmental issues;
- Government agencies run by elected and appointed officials who are charged with the responsibility for public safety;
- Industry, which comprises dangerous goods producers, carriers and consumers.

While the justification for this interest is quite obvious for the public and regulatory agencies, there are several motivating factors for industry to take this stance. Firstly, there is a strong campaign within industry to promote itself as a good corporate citizen, concerned about its place in the community and the nation. Secondly, industry may face prosecution, at least in theory, if they are found responsible for any incidents. Finally, even if legal liability cannot be attributed to a specific company, the public will consider that company to be at least partially accountable for the consequences of the incident, thereby tarnishing their public image [Lepofsky, Abkowitz, & Cheng, 1993].

2.1.3 Causes of dangerous goods transport incidents

Human error has been cited as a major cause of dangerous goods transport incidents [Harwood & Russell, 1989]. Releases from containment may occur during normal transport (en-route) or as a result of a traffic accident. En-route releases may be caused by: loose or defective fittings, tanker valve leakages, defects in the tanker welds or corrosion-induced container failure. Container failure also frequently occurs during loading and unloading operations [Abkowitz, List & Radwan, 1989]. En-route incidents, although taking place with some frequency, generally involve a minor loss of material and a low consequent damage. Although accident-related releases occur with much lower frequency than en-route releases, they may reflect more catastrophic failures with more extensive consequent damages [Saccomanno & Shortreed, 1993].

Harwood & Russell [1989] confirmed that traffic accidents are far more likely to result in severe dangerous goods incidents than other causes. They studied five years of data (1981-1985) from the U.S. Research and Special Programs Administration (RSPA) Hazardous Materials Incident Reporting system and identified factors that contributed to dangerous goods incidents. Traffic accidents were found to precipitate approximately 11 per-cent of all on-highway dangerous goods incidents. As driver error is a significant cause of traffic accidents [Harwood & Russell, 1989], "human error" is essentially responsible for a large proportion of the dangerous goods incidents presented in Table 2.1. When considering severe incidents only (deaths, injuries, etc.), traffic accidents were found to be the leading cause.

Table 2.1: Distribution of U.S. on-highway dangerous goods incidents by cause of release, 1981-1985 [Harwood & Russell, 1989]

Cause of dangerous goods release	**All reported incidents**		**Severe incidents only**	
	No.	**%**	**No.**	**%**
Traffic accident	1 457	10.8%	355	56.1%
Human error	6 845	50.5%	101	16.0%
Package failure	4 691	34.6%	128	20.2%
Other	550	4.1%	49	7.7%
Total	13 543	100%	633	100%

Harwood & Russell [1989] also noted that the predominant dangerous goods released were flammable and combustible liquids (46 per-cent) and corrosive materials (40 per-cent). Poisonous gases and liquids constituted 5 per-cent of all on-highway releases. Flammable and combustible liquids constituted 71 per-cent of releases due to traffic accidents. Corrosive materials accounted for only 13 per-cent of the releases due to traffic accidents, but 43 per-cent of the releases due to other causes. Hence, corrosive materials, by their very nature are much more likely to produce a valve, fitting or container failure than other dangerous goods [Harwood & Russell, 1989].

2.2 Challenges of Transporting Dangerous Goods in Urban Areas

There are several issues and problems associated with the movement of dangerous goods in urban areas.

2.2.1 Road geometrics

The common problems faced by heavy-vehicle drivers may be attributed to the poor geometrics of intersections and to obstacles along routes [ASCE, 1989]. The geometrics of many urban intersections are not adequate for accommodating the turning radius of large heavy vehicles and the off-tracking of their rear wheels. To make turns at these intersections large heavy vehicles must often cross the centreline and encroach on the portion of road meant for oncoming traffic; otherwise, the rear wheels may go over the kerb and cause damage. Telephone and utility poles and even traffic control signals are often located too close to the kerbside lanes where they can hinder the free movement of heavy vehicles. The problem of inadequate lateral clearance is more serious on roads with narrow lane widths and sharp curves, where heavy vehicles are forced to encroach on the adjacent lane [ASCE, 1989]. The majority of intersections in urban areas do not require special geometrics for large heavy vehicles because of the small number of heavy vehicles going through these locations. However, there are specific locations with high flows of large heavy vehicles in most urban areas.

2.2.2 Routing and scheduling

Major arterial routes in urban areas carry a large number of dangerous goods vehicles. In many cases, these routes pass through developed areas with residential developments located in close proximity. Routing involves the selection of paths through the transport network connecting the shipment origin and destination. The criteria for route selection may include avoiding high-accident locations, densely populated areas or heavily congested links [Abkowitz et al. 1989]. Routing decisions have significant implications on the level and distribution of the risk associated with dangerous goods shipments.

Pet-Armacost, Sepulveda & Sakude [1999], investigating the risks associated with transporting the chemical Hydrazine, found that routes that avoided large population centres actually placed more people at risk due to the longer route length, relatively higher accident frequencies and larger number of total kilometres travelled through small cities and towns. All-freeway routes were found to be less hazardous, both in terms of the number of adverse consequences and the population at risk.

Routing is further complicated by the fact that a route that is safe for the transportation of one type of dangerous substance may not be safe for the transportation of another as their hazard manifestations are different. Hazard manifestation refers to the plume size, shape, direction of movement and impact zone resulting from a dangerous goods release. Impact zones are areas in which a threshold chemical concentration is exceeded [Ashtakala & Eno, 1996].

Although certain communities may face high levels of risk from transportation routes with large dangerous goods flows, equally high levels of preparedness will have the effect of reducing the adverse consequences of dangerous goods releases and thus, overall vulnerability [Abkowitz et al. 1989].

Scheduling is also important to the routing problem, as it involves the timing of dangerous goods shipments. The objective of scheduling is to minimize the level of exposure caused by a given shipment or a collection of shipments. Potential scheduling actions include travel restrictions during peak hours or through heavy employment areas during the daytime and heavy residential areas at night. It may also be appropriate to avoid periods when schools are either starting or ending [Abkowitz et al. 1989].

Besides safety, another issue concerning dangerous goods routing is the transportation cost. Dangerous goods routing models that use only risk related criteria, or only cost related criteria, often fail to capture the conflict existing between risk and transportation cost. A route that minimizes risk may not coincide with a route that minimizes the heavy-vehicle operating cost [Zografos & Davis, 1989]. Thus, a trade-off exists between risk and carrier cost. Routing decisions are likely to increase the trip length for the carrier and scheduling restrictions are likely to increase the travel time, both of which increase the shipment cost. Eventually these cost increases are passed on to the consumer in the form of higher commodity prices [Abkowitz et al. 1989].

2.3 Risk Estimation

2.3.1 Individual and societal risk

There are two types of risk used in risk assessment: *individual risk* and *societal risk*. Individual risk is defined as the risk of harm to an individual, who is assumed to be in a particular position for all the time he/she is exposed to the risk. It measures the risk of harm at a given point. Individual risk is totally dependent upon the source of the risk. Societal risk shows the relationship between the frequency of an incident and the number of people harmed. Societal risk considers the distribution of people in the study area. Hence, societal risk is dependent on the source of the risk and the density and proximity of the public [Saccomanno & Shortreed, 1993].

2.3.2 Overview of accident, incident and exposure data

A dangerous goods transportation risk assessment requires a complete understanding of, and a careful distinction between *accident*, *incident* and *exposure* data. Exposure data in dangerous goods studies provide a measure of the opportunities for accidents and incidents to occur [Harwood & Russell, 1989]. Figure 2.1 presents a classification scheme for accidents and incidents.

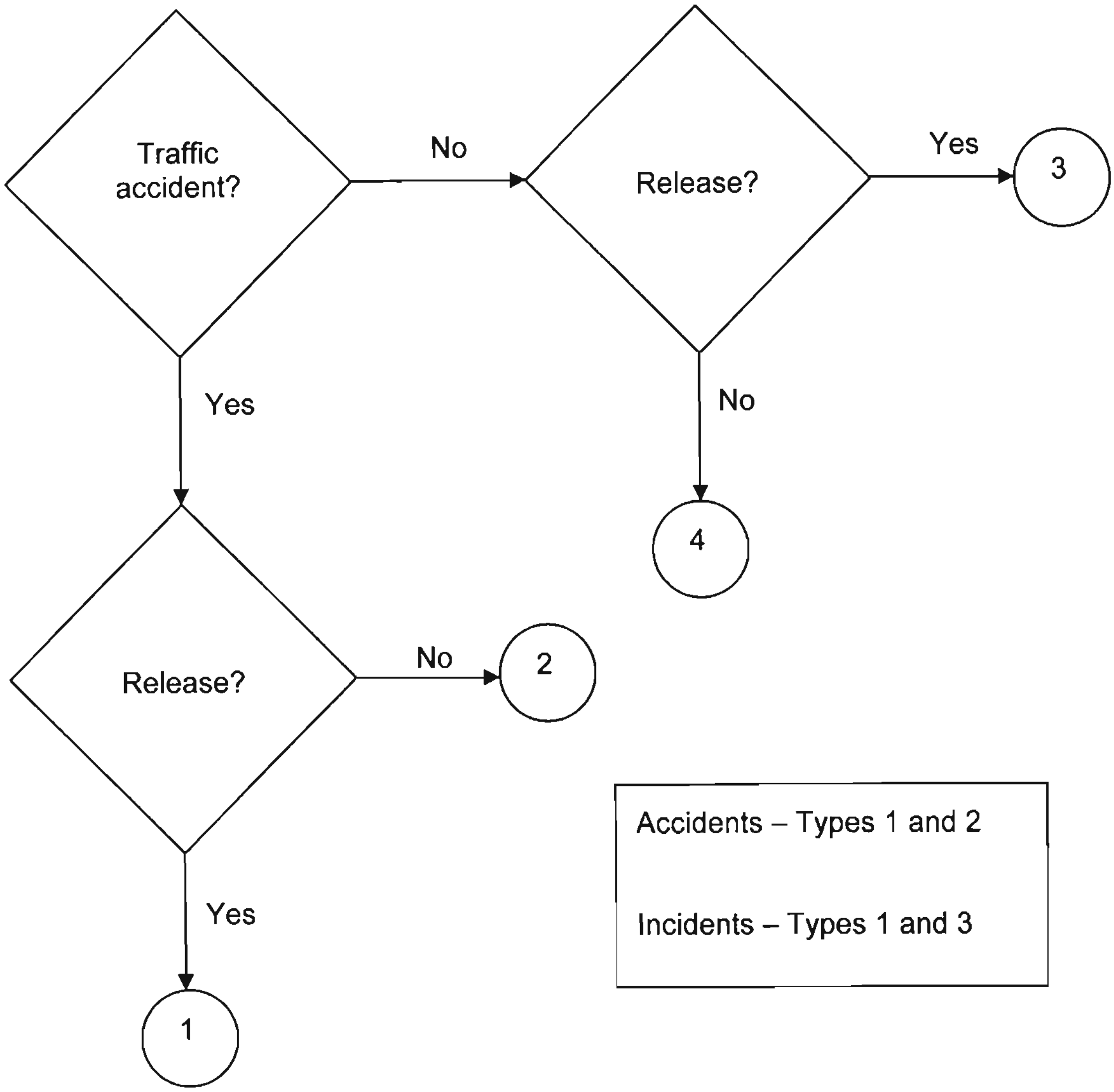


Figure 2.1: Classification scheme for on-highway events for heavy vehicles carrying dangerous goods [after Harwood & Russell, 1989]

Figure 2.2 further illustrates the overlapping nature of accidents and incidents. Figure 2.2 shows that exposure measured in *total highway trips* or *total highway vehicle-kilometres of travel* (represented by Block A) may be subdivided into three categories: dangerous goods shipments (B); other heavy-vehicle shipments that involve similar vehicles but do not involve dangerous goods (C); and highway travel by vehicle types other than heavy vehicles (D). Each highway shipment or trip may or may not involve a traffic accident. Dangerous goods shipments may also involve an incident (release) even if no accident occurs [Harwood & Russell, 1989]. Thus, Figure 2.2 illustrates: some incidents that are not accidents (F), some accidents that are not incidents (L), and some occurrences that are both incidents and accidents (M).

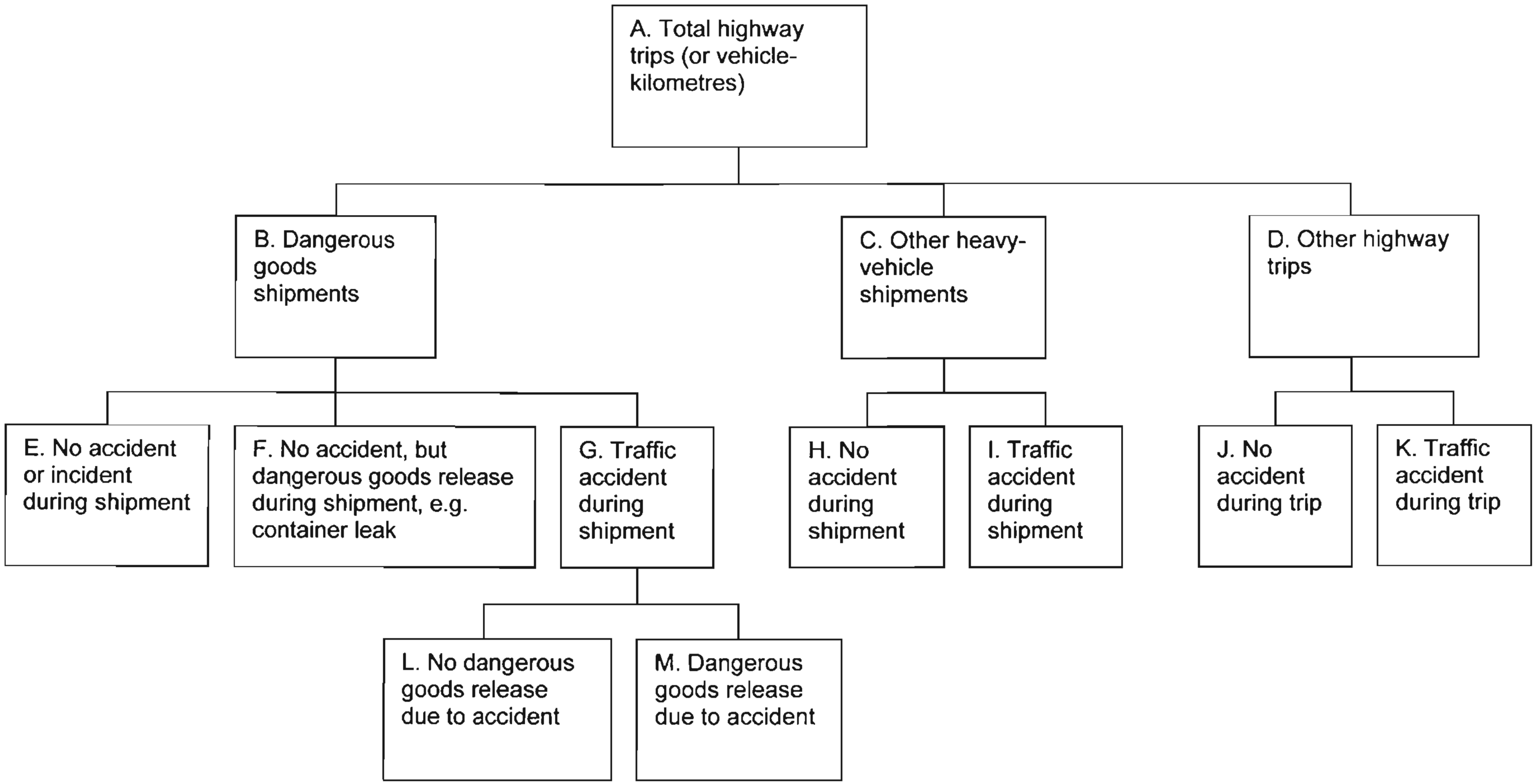


Figure 2.2: Relationships between accident, incident and exposure data [after Harwood & Russell, 1989]

2.3.3 The process of risk estimation

Risk estimation is a sequential process. It begins with understanding the level of exposure (e.g. number of dangerous goods shipments, type of material, trip lengths, tons carried), the frequency and type of incident occurrence (e.g. traffic accident, tanker rollover, loose fitting) and the consequence for a given incident (e.g. death, injury, property damage). The manner in which these factors are defined and measured depends on the data available, the purpose of the risk assessment and the preference of the risk analyst. The reliability of any dangerous goods transport safety assessment is only as good as the quality of the available data. Information is needed on three aspects of the problem: flows of dangerous goods; incidents and accidents; and the population at risk. Census data are standard and readily available. Hence, the need for quality and consistency lies mainly with the first two data categories [Harwood & Russell, 1989].

A major stumbling block in heavy-vehicle safety research is that exposure data that correspond well to the available accident data are seldom available. For example, suppose that accident data were obtained for all highways in a particular province broken down by highway type, heavy-vehicle type (single-unit heavy vehicles, articulated heavy vehicles, multiple-articulated heavy vehicles) and cargo area configuration (flatbed, tanker, ISO-tainer, etc.). In order to establish accident rates for these variables, exposure data broken down by the same factors would be needed. Heavy-vehicle exposure data of this type is unlikely to be available [Harwood & Russell, 1989].

Data on the movement of dangerous goods by heavy vehicles into and through urban areas, as well as the number and nature of dangerous goods incidents, is difficult to obtain. Due to the cost and difficulty of collecting corresponding exposure data, it is often necessary to make exposure estimates from data sources that are independent of, and not intended for use with, the available accident and incident data [Harwood & Russell, 1989]. Hence, many transportation studies have utilised whatever historical data is available without concern for the quality of the data, its uncertainties and biases [Abkowitz et al. 1989].

An intensive risk analysis should consider the activities of non-residential areas, such as industry, services, commerce, education, health and social activities, sport and cultural activities and transportation. Importance should be placed on the more vulnerable zones in an area in the event of an incident. The more vulnerable zones are places that concentrate a large number of people who are difficult to protect or evacuate, e.g. schools, hospitals or commercial centres [Lassarre, Fedra & Weigkricht, 1993].

Expressing risk in terms of a single number may simplify the tasks of estimation and evaluation, but it does not provide as much information as a risk profile, which is a probability distribution of incident likelihood and consequence. The shape of the risk profile helps in distinguishing between the contribution of high probability/low consequence events and the contribution of low probability/high consequence events to the estimated risk [Abkowitz et al. 1989].

The term *Risk* has been used repeatedly as a measure of relative safety and is the basis for transportation hazard analysis. Lepofsky, Abkowitz, & Cheng [1993] defined *risk* as a combination of *accident likelihood*, *release probability*, *consequence of release* and *risk preference*.

Accident likelihood is a function of the characteristics of the driver, the vehicle, the transportation network and other external effects. The likelihood of an accident is often represented as the *accident rate* for a transportation segment and is defined to be the number of accidents over some measure of exposure, such as vehicle-kilometres of travel. Deciding on the appropriate accident rate for use in the analysis, and finding a means for estimating the level of exposure is crucial. The accident rate cannot be estimated without somehow estimating how many accidents did not occur. This is usually done by obtaining estimates on the number of vehicle-kilometres of travel that occurred on the portion of the transportation network for which the accident statistics were obtained [Lepofsky et al. 1993].

The *probability of a release*, given a dangerous goods accident, is associated with the characteristics of the container in which the material is being transported. There is a relationship between the cargo type, the container type and the mechanics of the accident [Lepofsky et al. 1993].

The *consequences* of an incident are usually measured in terms of the population exposed, but could be extended to include expected injuries or fatalities, cost of property damage, or the extent of environmentally sensitive areas that are affected [Lepofsky et al. 1993].

Risk preference is used to adjust risk measurement to better reflect the attitudes of a particular interest group. Risk preference is difficult to quantify as it is based on public perception. Each interest group has a different perspective on the issues and consequences of dangerous goods transportation. For example, the general public has tended to be more concerned about a single accident in which fifty people are killed, than fifty separate accidents, each of which results in a single fatality. The public's association of a higher perceived risk with more catastrophic incidents is representative of risk-averse behaviour. *Risk neutral*, which is used to represent technical risk, is the risk estimated without any modifications for risk preference [Lepofsky et al. 1993].

Lepofsky et al. [1993] used the following equation to describe the relationship between the components of risk:

$$Risk = (Accident\ likelihood) \times (Release\ probability) \times (Consequences)^{Risk\ preference} \qquad (2.1)$$

The first two terms in Equation (2.1) are used to predict the release-causing accident rate, which is the likelihood of an accident for a given shipment multiplied by the likelihood of a release given an accident. A neutral risk preference is represented by an exponent value of one. Values of risk preference greater than one will cause consequences to be weighted more heavily and would result in a risk-averse analysis [Lepofsky et al. 1993].

2.3.4 Effects of risk aversion

In the context of dangerous goods transport, although every incident is likely to receive media attention, a very large incident, for example, one that requires the evacuation of one thousand people, may receive disproportionate attention. Such an incident and the resulting public scrutiny, may result in very significant costs (financial and public image) to the shipper and carrier, perhaps even in the imposition of new restrictions on shipments. It may be in the best interests of a carrier to avoid such incidents if at all possible. An incident affecting one thousand people may well be more than one hundred times costlier than an incident affecting ten people, in terms of financial cost and tarnished public image. Consequently, a carrier may prefer a route involving a one-in-a-thousand chance of an incident that affects ten people, to a one-in-a-hundred-thousand chance of an incident affecting a one thousand people [Erkut & Ingolfsson, 2000].

Perhaps the most obvious example of risk averse behaviour is the attention directed to airplane crashes. Many more people die in highways accidents than in airplane accidents. Furthermore, travel by aeroplane is considerably safer than driving for trip lengths where air travel is a realistic alternative. However, almost every aeroplane crash makes it to the news media, whereas most highway accidents do not [Erkut & Ingolfsson, 2000].

2.4 Heavy-vehicle Accident Rate Models

To conduct risk assessments for the road transportation of dangerous goods, estimates of accident and release rates are essential. Published literature underscores the importance of these rates in risk assessment, as well as the shortcomings of the available data. Reliable data on heavy-vehicle accident rates is a key element for use in establishing the relative probabilities of dangerous goods releases [FHWA, 1989].

2.4.1 Heavy-vehicle accident rate models for route segments

The U.S. Department of Transportation (USDOT) has published guidelines, which include a risk assessment model, for identifying preferred routes for the transportation of dangerous goods [FHWA, 1989]. Harwood, Viner & Russell [1993] pointed out several weaknesses in the accident probability portion of these USDOT guidelines. These weaknesses include:

- The guidelines are based on accident predictive models that apply to accident rates for all vehicle types, rather than to heavy-vehicle accident rates. All-vehicle accident rates are based primarily on passenger car accidents, even though the highway transportation of dangerous goods is conducted primarily by heavy vehicles.
- The USDOT guidelines implicitly assume that all accidents have an equal likelihood of resulting in a dangerous goods release. Research has established that certain types of accidents are more likely than others to result in a release.
- The guidelines recommend the use of observed accident rates for the specific route segments under analysis, whenever possible, in preference to default values given for the route segment type. However, no statistical guidance is given on whether the observed accident rate is based on a sufficiently large sample to be statistically reliable; or whether the differences between the observed accident rates and the default values are statistically significant.

Harwood et al. [1993], taking into cognisance these weaknesses in the USDOT guidelines, developed heavy-vehicle accident rates as a function of roadway type and area type. Harwood et al. [1993] studied databases containing information on highway geometrics, heavy-vehicle volumes and heavy-vehicle accidents for the entire state highway system of three U.S. states: California, Illinois, and Michigan. This information is summarised in Table 2.2. These states were chosen because they had computer files that were the most complete and easy to integrate. The unit of measurement commonly used for heavy-vehicle accident rate on links or road segments is *accidents per million vehicle-kilometres*. It is evident from Table 2.2 that there are substantial variations in accident rate among the three states. According to Harwood et al. [1993], this is the case for most accident studies. Accident rates for seemingly identical conditions in different U.S. states can differ by a factor as large as three or four. Such differences may arise due to differences in the accident reporting systems of the various states or due to a particular highway class in a state having a small sample size of heavy-vehicle accident involvements or heavy-vehicle travel. In order to minimise the influence of values based on small sample sizes, the heavy-vehicle accident rates in Table 2.2 were weighted by vehicle-kilometres of travel to obtain a weighted average.

The authors concluded that the three-state weighted averages presented in Table 2.2 adequately represent the relative differences in risk between highway classes and are appropriate for use as default values of heavy-vehicle accident rate when no better local estimates are available. However, Harwood et al. [1993] strongly encouraged the development of default values from regional data, wherever possible.

Table 2.2: Heavy-vehicle accident rates for use as default values [Harwood et al. 1993]

Area type	Roadway type	Heavy-vehicle Accident Rate [Accidents per million vehicle-km]			
		California	Illinois	Michigan	Weighted average
Rural	Two-lane	1.07	1.94	1.33	1.36
Rural	Multilane undivided	3.38	1.32	5.90	2.79
Rural	Multilane divided	0.76	2.98	3.52	1.34
Rural	Freeway	0.33	0.29	0.73	0.40
Urban	Two-lane	2.63	6.90	6.79	5.38
Urban	Multilane undivided	8.09	10.59	6.44	8.65
Urban	Multilane divided	2.17	9.20	6.59	7.75
Urban	One-way street	4.10	16.38	5.02	6.03
Urban	Freeway	0.99	3.62	1.74	1.35

The heavy-vehicle accident rates for each highway class were estimated by Harwood et al. [1993] as follows:

$$TAR_j = \sum_i \frac{A_{ij}}{VKT_{ij}} \tag{2.2}$$

where:

TAR_j = Heavy-vehicle accident rate for highway class j

A_{ij} = number of heavy-vehicle accident involvements in one year on route segment i in highway class j (accidents involving two or more heavy vehicles are counted as two or more involvements)

VKT_{ij} = annual vehicle-kilometres of travel on route segment i in highway class j (obtained by multiplying the length of segment i by the heavy-vehicle Annual Average Daily Traffic volume)

2.4.2 Probability of release given an accident

There is a need to consider incident likelihood and severity in safety analyses [Abkowitz et al. 1989]. An accident involving a dangerous goods carrying heavy vehicle cannot lead to potentially catastrophic consequences unless the dangerous goods being transported are released. The probability of a release, given that an accident involving a dangerous goods carrying heavy vehicle has occurred, varies with the type of accident. The dangerous goods release probabilities presented in Table 2.3 were developed by Harwood et al. [1993] using information from the U.S. Federal Highway Administration heavy-vehicle accident databases.

Table 2.3: Probability of release as function of accident type, given that an accident has occurred [Harwood et al, 1993]

	Accident type	Probability of dangerous goods release given accident
Single-vehicle non-collision accidents	Run-off-road	0.331
	Overturned (in road)	0.375
	Other non-collision	0.169
Single-vehicle collision accidents	Collision with parked vehicle	0.031
	Collision with train	0.455
	Collision with non-motorist	0.015
	Collision with fixed object	0.129
	Other collision	0.059
Multiple-vehicle collision accidents	Collision with passenger car	0.035
	Collision with heavy vehicle	0.094
	Collision with other vehicle	0.037

The distribution of accident types varied markedly between highway classes. For example, the percentage of single vehicle non-collision accidents (which had the highest probability of producing a dangerous goods release if an accident occurs) was approximately twice as high on rural highways as on urban highways.

The probability of a release, given an accident involving a dangerous goods carrying heavy vehicle, for a particular highway class was estimated by Harwood et al. [1993] as:

$$P(R \mid A)_j = \sum_k P(R \mid A)_k \times P(k)_j \qquad (2.3)$$

where:

$P(R|A)_j$ = probability of a dangerous goods release given an accident involving a dangerous goods carrying heavy vehicle, for highway class j

$P(R|A)_k$ = probability of a dangerous goods release given an accident involving a dangerous goods carrying heavy vehicle, for accident type k (from Table 2.3 or equivalent regional data)

$P(k)_j$ = probability that an accident on highway class j will be of accident type k

Harwood et al. [1993] developed default values for the probability of a dangerous goods release, given that an accident has occurred on a particular highway class. Harwood et al. [1993] concluded that the three-state weighted averages presented in Table 2.4, are appropriate for use as default values when no better local estimates are available. However, Harwood et al. [1993] strongly encouraged the development of default values from regional data, wherever possible.

Table 2.4: Probability of a dangerous goods release given an accident, as a function of highway class, for use as default values [Harwood et al, 1993]

Area type	Roadway type	Probability of dangerous goods release given an accident
Rural	Two-lane	0.086
Rural	Multilane undivided	0.081
Rural	Multilane divided	0.082
Rural	Freeway	0.090
Urban	Two-lane	0.069
Urban	Multilane undivided	0.055
Urban	Multilane divided	0.062
Urban	One-way street	0.056
Urban	Freeway	0.062

2.4.3 Releasing accident rate

Harwood et al. [1993] presented Table 2.5, which gives typical values of *Releasing Accident Rate, Heavy-vehicle Accident Rate* and *Probability of Release* that may be used as default values.

The *Releasing Accident Rate* was estimated by Harwood et al. [1993] as:

$$RAR_j = TAR_j \times P(R \mid A)_j \tag{2.4}$$

where:

RAR_j = Releasing Accident Rate for highway class j

TAR_j = average Heavy-vehicle Accident Rate for highway class j

$P(R|A)_j$ = Probability of a dangerous goods release given an accident involving a dangerous goods carrying heavy vehicle, for highway class j

Table 2.5: Default heavy-vehicle accident and release rates [Harwood et al. 1993]

Area type	Roadway type	Heavy-vehicle accident rate [Accidents per million vehicle-km]	Probability of dangerous goods release given an accident	Releasing accident rate [Releases per million vehicle-km]
Rural	Two-lane	1.36	0.086	0.12
Rural	Multilane undivided	2.79	0.081	0.22
Rural	Multilane divided	1.34	0.082	0.11
Rural	Freeway	0.40	0.090	0.04
Urban	Two-lane	5.38	0.069	0.37
Urban	Multilane undivided	8.65	0.055	0.48
Urban	Multilane divided	7.75	0.062	0.48
Urban	One-way street	6.03	0.056	0.34
Urban	Freeway	1.35	0.062	0.09

2.4.4 Statistical guidance on use of local accident rates

Harwood et al. [1993] stated that there is a need for caution in using accident rates based on small sample sizes of accidents, which are typical of relatively short route segments. For example, consider three route segments of one kilometre length. Suppose that in a three-year period, Segment 1 experiences zero heavy-vehicle accidents, Segment 2 experiences one heavy-vehicle accident and Segment 3 experiences two heavy-vehicle accidents. It would be incorrect to treat Segment 1 as having zero risk of a dangerous goods release. It would also be incorrect to presume that, since Segment 3 had twice as many accidents as Segment 2, it also has twice as much risk [Harwood et al. 1993]. Since accident occurrence is a random variable, site-specific accident data cannot be presumed to indicate true differences in risk between segments unless a statistical test indicates that these differences are significant. The default heavy-vehicle accident rates from Table 2.5, or preferably, average regional values should be used to estimate heavy-vehicle accident rates. According to Harwood et al. [1993], a statistical procedure based on the Chi-squared (χ^2) test may be used to establish whether the actual accident frequency for a particular route segment is sufficiently larger or smaller than the expected accident frequency to warrant replacement of the default heavy-vehicle accident rates by site-specific rates based on accident histories. The test is performed by calculating the value of the Chi-squared (χ^2) statistic:

$$\chi^2 = \frac{(A_E - A_O)^2}{A_E} \tag{2.5}$$

where:

χ^2 = Chi-squared statistic

A_E = expected number of heavy-vehicle accidents

A_O = observed number of heavy-vehicle accidents

If $\chi^2 \leq 4$, then the expected and observed number of heavy-vehicle accidents do not differ significantly at the 95 per-cent confidence level. Therefore, the system-wide default accident rate should be preferred to the site-specific data. If $\chi^2 > 4$, then the expected and observed numbers of heavy-vehicle accidents differ significantly [Harwood et al. 1993], i.e. at the 95 per-cent confidence level, the observed accident rate is lower or higher than the system-wide default value. In this case, the system-wide default accident rate should be replaced by a value based on the site-specific data. If the site-specific accident rate is greater than the default accident rate, then the site-specific rate should be used. If the site-specific accident rate is less than 50 per-cent of the default accident rate, then 50 per-cent of the default accident rate should be used. The latter restriction is included to keep very low short-term accident experience, or poor accident reporting levels in a particular area, from disproportionately affecting the results. Even if a roadway segment has experienced no accidents during the study period, there is still risk involved in transporting dangerous goods over this segment and the use of 50 per-cent of the default accident rate is recommended by Harwood et al. [1993].

2.5 Application of Dispersion Modelling

The dispersion modelling process, a major component of risk analysis, has been undergoing continuous refinement in recent years. This is evident in the number of commercially available products that perform some type of dispersion modelling [US-EPA, 1998].

The dangerous goods of interest to this investigation are those that could give rise to dispersing vapour clouds upon release into the atmosphere. These could subsequently cause harm through inhalation or absorption through the skin. When a release of dangerous goods occurs, a dispersion model may be utilised to estimate the plume size, shape and direction of movement of dangerous substance resulting from the spill. By combining information on the spill characteristics, material properties and meteorological and topographical parameters, the hazard zone affected by a release of dangerous goods may be estimated using a dispersion model. Hazard zones are areas in which a threshold chemical concentration is exceeded. The chemical itself governs many of the health consequences of an incident. By comparing the ambient temperature and the boiling point of the chemical, the initial state (liquid or gas) in which a material is released into the atmosphere, may be forecast. The molecular weight may be used to estimate concentrations under varying release rates. Dose relationships estimate the severity of the hazard to humans. These are expressed as concentrations that will result in exposure, injuries and fatalities [CERC, 2001].

Meteorological conditions interact with material properties to define the characteristics of the plume. The direction of the wind, if any wind is present, governs the direction in which the airborne contaminants will move. The wind speed is used to estimate the plume's downwind distance as a function of time and also affects the extent to which the plume expands perpendicular to its direction of travel, i.e. the plume spread. The stability of the atmosphere is also a factor in the expansion of the plume. The more turbulent the air, the more extensive is the area of dispersion [Pasquill & Smith, 1983]. When multiple potential dangerous goods incidents are investigated for planning or risk assessment purposes, historical distributions of meteorological conditions may be used to estimate the dispersion effects of each release scenario. Topographical data may enhance the accuracy of dispersion modelling by providing a more precise representation of a release scenario [CERC, 2001].

The use of dispersion modelling enables a sophisticated risk assessment approach, leading to estimation of expected injuries or fatalities instead of simple population exposure. When applied over a range of incident scenarios, risk profiles may be generated that combine the consequences for various scenarios based on their likelihood. Risk profiles portray the relationship between incident likelihood and severity. Intuitively, a given accident will yield a profile in which there are a large number of possible scenarios that result in low or moderate casualties and a smaller number of scenarios that will result in a very high number of casualties. The consequences of a spill may be expressed per shipment of dangerous goods. Therefore, in order to compare the risk of a given dangerous goods shipment to other risks, e.g. the risk of being involved in a passenger car accident or being struck by lightning, the number of shipments per year (or some other appropriate time interval) should be considered [Lepofsky et al. 1993].

2.6 Application of Geographical Information Systems

2.6.1 The nature of geographic information systems (GIS)

Risk assessment of dangerous goods transportation involves an assessment of the following [Lassarre, Fedra & Weigkricht, 1993]:

- The potential hazards of the substances involved.
- The packaging aspects.
- The vehicle and route selection in relation to accident probabilities.
- The operational aspects of transportation, such as speed limits, restrictions to daytime mobilization, or certain weather conditions.
- The environment around the network in terms of general land use, population density and vulnerable installations such as schools or hospitals.

The analysis of dangerous goods transportation flows, accident scenarios and impacts are related to the road network, whereas the exposure analysis is related to the surroundings of the road network. Hence, the simulation of activities related to transportation requires not only detailed information about the road network, but also geographical and environmental data. These categories lend themselves to representation and manipulation by means of geographical information systems [Lassarre et al. 1993]. Abkowitz, Cheng & Lepofsky [1990a] illustrated the use of geographic information systems (GIS). They found that GIS is ideally suited to dangerous goods routing and risk assessment.

Geographic information systems may be applied to sophisticated transportation management problems, some of which may require real-time decision-making. Two applications have been identified: the management of dangerous goods highway incidents and transportation hazard analysis. Highway incident management includes emergency response deployment and the rerouting of traffic to bypass the affected area. Transportation hazard analysis includes the routing of dangerous goods shipments and emergency preparedness in the case of a dangerous goods release, and involves comprehensive risk assessment and evacuation planning [Lepofsky et al. 1993].

The nature of GIS itself makes sophisticated transportation management analysis possible. With GIS, detailed transportation networks that incorporate both physical and operational characteristics may be developed or obtained. Complicated analyses may be performed efficiently by combining information describing the transportation network, specific chemicals, historical meteorological conditions and population distribution into an integrated environment [Lepofsky et al. 1993].

The use of geographical information systems can thus enhance dispersion modelling by extending analysis capability. Through integrating plume representation with population data and maps of the transportation system, the consequences and population exposure may be estimated more efficiently. Without this integration, plume coordinates must be transferred to another system or census map and the affected population must be *counted* [Lepofsky et al. 1993].

The evacuation planning capability of GIS may be used in real-time to influence area-wide evacuation strategies in the event of a dangerous goods incident. After first identifying the area at risk using a dispersion model, and with the transportation network overlaid, GIS may be used to identify the most efficient method for evacuating an area. Traffic volumes and densities may be used to estimate existing roadway utilization and the potential for accommodating additional traffic that must be rerouted from other roads affected by the incident. This is a dynamic process and the growing plume may be used to eliminate roadways from the evacuation network as they become exposed as a function of time [Lepofsky et al. 1993].

2.6.2 Case study

To illustrate the application of a GIS to transportation hazard analysis and managing dangerous goods shipments, Lepofsky et al. [1993] presented a case study. Lepofsky et al. [1993] illustrated the application of GIS to vehicle routing on the transportation system. The transportation of a shipment of rocket fuel between an origin-destination pair in the state of California, U.S. was used as an example. GIS provides the ability to select preferred routes between an origin-destination pair based on efficiency, safety or a combination of the two. Travel time, which takes into account the operational characteristics of a route, was used as a measure of efficiency instead of travel distance. For example, a route passing through a densely populated urban area may be shorter in length than a route using circumferential highways; however, the urban route might incur travel time penalties due to congestion. Road segments within the state were selected and the segment distance was divided by the average operating speed to yield the travel time for the segment. The risk of population exposure within an eight-kilometre band around each road segment was used as the measure of safety. Using different combinations of weights on the two criteria resulted in the identification of distinct route alternatives, i.e. weighting the analysis entirely on minimising travel time produced a very different route than if risk minimisation were the dominant criterion. Weighting each criterion equally resulted in another alternative. Table 2.6 presents the impact measures corresponding to routes identified based on three different weighting alternatives.

Table 2.6: Routing analysis impact measures [Lepofsky et al. 1993]

Path	Objective to minimise	Distance (km)	Travel time	Population exposed
1	100% travel time	625	7 hours, 54 min	3 059 408
2	50% travel time, 50% risk	699	8 hours, 10 min	819 687
3	25% travel time, 75% risk	792	8 hours, 31 min	214 960

A comparison of the resulting routes showed that with only a small increase in travel time, the number of people exposed could be drastically reduced, e.g. Path 2 reduced the population exposed by almost 75 per-cent and only resulted in a 3.4 per-cent increase in travel time over the quickest route. Hence, with a routing analysis, a shipment of dangerous goods may be routed so as to reduce the negative impacts on the public, without significantly increasing the financial burden on the carrier Lepofsky et al. [1993].

2.7 Application of Monte Carlo Simulation

2.7.1 Models and simulation

A model is a mathematical representation of a physical process, i.e. models are an abstraction of reality. Modelling is a fundamental tool of science, engineering and business. Models generally have limits of credibility [Kalos & Whitlock, 1986]. A model may be used to make predictions and try "What If?" scenarios. Changing the inputs and recalculating the model may generate a new answer. Computers have made it possible to create models that simulate reality and aid in making predictions. One of the methods for simulating real systems is the ability to take into account randomness by investigating many different scenarios. The results of these scenarios can then be compiled and used to make decisions [Pet-Armacost, Sepulveda & Sakude, 1999].

A simulation is a type of model where the computer is used to imitate the behaviour of a physical process. Simulation is often the only type of model possible for complex systems. The process of building a simulation can clarify the investigator's understanding of the real system. This is sometimes more useful than the actual application of the final simulation. Simulation allows for sensitivity analysis and optimisation of a real system without need to operate the real system. With a simulation the investigator can maintain better control over experimental conditions and can evaluate the system on a slower or faster time scale than the real system [Kalos & Whitlock, 1986].

However, a simulation may be very expensive and time consuming to build. It is easy to misuse a simulation by “stretching” it beyond the limits of credibility. This problem is apparent when using commercial simulation packages, due to their ease of use and the lack of familiarity with the underlying assumptions and restrictions. Fancy graphics, animation, tables, etc. may tempt the user to assign unwarranted credibility to the output [Pet-Armacost et al. 1999].

2.7.2 Monte Carlo simulation

Scientists, engineers, statisticians, managers, investors, etc. have employed Monte Carlo simulation to investigate issues in the following fields: business modelling, decision analysis, risk analysis, management science, project management, real options analysis, and others [Pet-Armacost et al. 1999].

Monte Carlo simulation is a stochastic technique, i.e. it is based on the use of random numbers and probability statistics to investigate problems. A model created with a spreadsheet like *Microsoft Excel*™, has certain input parameters, and equations that use those inputs to produce a set of outputs. This type of model is typically deterministic, i.e. if the input parameters are held constant, the same results are obtained no matter how many times the model is recalculated. Monte Carlo simulation is a method for iteratively evaluating a deterministic model using sets of random numbers as inputs. This method is often used when the model is complex, non-linear, or involves multiple uncertain parameters [Kalos & Whitlock, 1986].

Monte Carlo simulation may be used to establish how random variation, lack of knowledge, or error affects the reliability, performance or sensitivity of the system that is being modelled. It provides approximate solutions to a variety of mathematical problems. Monte Carlo simulation is a sampling method; the inputs are randomly generated from probability distributions to simulate the process of sampling from an actual population. A distribution is chosen for each input parameter that closely matches the existing data, or best represents the current state of knowledge. The data generated from the simulation may be represented as probability distributions (or histograms) or converted to tolerance zones, confidence intervals, error bars, and reliability predictions [Kalos & Whitlock, 1986].

2.7.3 Case study

Pet-Armacost et al. [1999] employed Monte Carlo simulation to investigate the risks associated with transporting the chemical Hydrazine in tanks, with and without relief devices fitted. Relief devices are used on tankers transporting flammable dangerous goods in order to prevent an explosion in the case where pressures in the tank become too high, e.g., in an accident where fire is involved. Relief devices are designed to release pressure (and vapour or liquid) when the pressure in the tank reaches a certain threshold [Pet-Armacost et al. 1999]. Hence, in the case of toxic substances, there is an increased risk of toxic exposures associated with containers fitted with relief devices. Hydrazine is highly toxic and flammable, as well as corrosive. Therefore, there was a conflict as to whether a relief device should be used or not.

No historical data was available on the impact of relief devices on release probabilities and subsequent toxic exposures, or on the impact of Hydrazine on the likelihood of fires and explosions. A Monte Carlo sensitivity analysis was employed to assess the impacts of these unknown parameters on the risk of toxic exposures, fires and explosions. The results of this study were utilised to make a policy decision regarding the use of relief valves in Hydrazine transportation. Pet-Armacost et al. [1999] concluded that the Monte Carlo simulation approach used in the study could be applicable to a broad range of problems involving estimation of transportation risks and routing decisions, even when there are substantial data uncertainties.

2.8 Previous Studies and Risk Assessment Models

Several other studies on the transportation of dangerous goods have been reported in the literature. They relate to aspects such as database development, selecting criteria for designating routes for transporting dangerous goods, etc. A selection of these studies is highlighted in this section.

Abkowitz, Cheng & Lepofsky [1990b] studied the impact of using alternative criteria and weights for route selection. Purdy [1993] developed a methodology for risk analysis of the transportation of toxic and flammable substances by road or rail as part of a major study in Britain. Stewart, Van Aerde & Shortreed [1990] created a computer model called *RISKMOD* to provide estimates of the risk associated with the transportation of dangerous goods by road and by rail. Pijawka, Foote & Soesilo [1985] developed a model for dangerous goods risk management and proposed a risk score for individual routes which reflected the interaction of a number of variables: the number of hazard events on a route, dangerous goods accident probability, population at risk and volume of dangerous goods by class. Saccomanno, Shortreed & Mehta [1990] performed a study of fatality rates and hazard areas for transporting Liquefied Petroleum Gas and Chlorine by heavy vehicle. Given the spill size, various damage propagation models were developed to establish the corresponding hazard areas associated with 50 per-cent and 1 per-cent damage.

Most of the existing dangerous goods routing models assume that the links of the transportation network have unlimited capacity to carry dangerous goods shipments. This assumption could lead to a small number of network links accommodating the network-wide flow of dangerous goods shipments. An immediate effect of such a routing procedure is the assignment of high risk to the population residing along these links, which fails to capture the aim of the equitable distribution of risk. Hence, Zografos & Davis [1989] developed a multi-objective decision-making model to mathematically formulate the routing of dangerous goods on the transportation network. The model included criteria relating to minimization of risk, minimization of risk to special populations, minimization of travel time and minimization of property damages.

Everitt [2004] examined the status of dangerous goods transport in South Africa. An assessment was made of toxic gas dispersion risk using a case study. The population affected by a worst-case scenario release for a section of the N3 highway was estimated. This included a comparison of the number of motorists affected versus the exposed population in the communities adjacent to the road.

2.8.1 Lassarre, Fedra and Weigkricht model

Lassarre et al. [1993] developed software based on GIS to manage, treat and represent statistical and geographical data related to the evaluation of dangerous goods transportation risk on a road network.

For a link on a network, Lassarre et al. [1993] defined the accident rate as the frequency of occurrence of an accident involving a vehicle transporting dangerous goods, multiplied by the length of the link. This rate was expressed as the number of accidents per vehicle-kilometres and varied according to the road category of the link. The direct estimation of this accident rate was difficult due to the lack of statistics for accidents involving dangerous goods and the lack of information about the number of vehicles transporting dangerous goods. To estimate this rate, the heavy-vehicle accident rate for different road categories and locations (urban and rural areas) was evaluated and multiplied by a factor specific to dangerous goods (usually less than one) to obtain the rate of accidents involving heavy vehicles transporting dangerous goods. This lead Lassarre et al. [1993] to the following estimates of accident rates (in units of accidents per 10^7 vehicle-kilometres) on four road categories: 2.5 on motorways, 7.5 on national roads and 12.5 on secondary roads and other roads. The risk calculation by Lassarre et al. [1993] was based on a daytime weekday situation.

For a link, the density (in units of vehicles per kilometre) was fixed to: forty for motorways, twenty for national roads, five for secondary roads and one for other road types. The vehicle occupancy rate was fixed to 1.8 persons per vehicle.

Lassarre et al. [1993] defined the consequences *C*, by the integral of the density of the exposed population *ρ*, over an impact zone *E*. Hence:

$$C = \int_E \rho(e)de \tag{2.6}$$

The exposed population could be concentrated on a site, distributed along a link or distributed over an area. If the density is constant over the impact zone, then:

$$C = \rho \times \mu(e) \tag{2.7}$$

With *μ* taken as an estimate of *E*.

- If *E* is a site, then $\mu(E) = 1$
- If *E* is a link, then $\mu(E) = L$, the length of the link
- If *E* is an area, then $\mu(E) = S(E)$, the area of the exposed surface

For the population exposed, *ρ* is:

- For a site, the number of people allocated to that site
- For a link of the network, the density of vehicles per kilometre on that section multiplied by the number of occupants per vehicle
- For an area, the population density per unit of surface area exposed

2.8.2 Ashtakala and Eno model

Ashtakala & Eno [1996] developed a model to select the route, which minimises risk to population, for transporting a specific dangerous substance between a point of origin and a point of destination (O-D pair) in a study area. Dangerous goods from three different classes, namely Chlorine gas, Liquefied Petroleum Gas (LPG) and Sulphuric Acid were chosen for study. The minimum risk routes between an O-D pair were established by using population risk units as link impedances. The risk units for each link were estimated by considering the probability of an accident and its consequences on that link. Their results showed that between the same O-D pair, the minimum risk routes were different for different dangerous goods. Hence, it is not possible and not realistic to designate a single route for the transportation of all types of dangerous goods [Ashtakala & Eno, 1996].

In the Ashtakala and Eno [1996] model, a significant amount of data on the highway network was required to compute risk units on the links. The highway network was coded in terms of links (road sections), nodes (intersections) and the attributes for individual links (distance, risk units, etc.). The number of people exposed to the dangers of dangerous goods was limited to an evacuation area on both sides of the road. An evacuation distance of five hundred metres on each side of the road was used, resulting in an evacuation width of one kilometre. The evacuation width multiplied by the length of the link gave the evacuation area of the link. The population density multiplied by the evacuation area gave the number of people affected on the link. The population densities corresponding to each link were obtained by integrating the demographic map and the highway map. Table 2.7 presents distance, traffic volume, dangerous goods Releasing Accident Rate (RAR), heavy-vehicle volume, accident probability and risk units for LPG for a sample link on the highway network.

Table 2.7: Population risk units on link [Ashtakala & Eno, 1996]

Node from	**Node to**	**Distance** [km]	**Population** [persons / km^2]	**Traffic volume** [vehicles /day]	**RAR** [releases per 10^6 vehicle-km]	**Heavy-vehicle volume** [heavy vehicles/day]	**Accident probability**	**LPG population risk units** [fatalities]
1	2	38	62	1526	0.124	183	0.31	0.029

Ashtakala & Eno [1996] defined risk as follows:

$$Risk = (Accident\ probability) \times (Accident\ consequences) \qquad (2.8)$$

Accident probability was estimated from traffic accident rates and traffic volumes. The consequences of an accident were estimated using a dispersion model specific to the dangerous substance. The consequent damages were expressed only in terms of immediate impacts. For different types of dangerous goods, the corresponding hazard area was affected by the release rate and release volume, duration of release, material properties and meteorological conditions. Saccomanno, Shortreed & Mehta [1990] reported hazard areas and fatalities for different release profiles on the road and these were used in computing accident consequences by Ashtakala & Eno [1996]. Risk was expressed in the number of fatalities and injuries to population. In this manner, the risk to population was estimated in terms of numerical units, which were termed population risk units.

The availability of heavy-vehicle accident rates and release probabilities permitted the estimation of the probability of a dangerous goods accident in which a release occurred. The probability of a dangerous goods releasing accident was estimated using the following equation, developed by Harwood et al. [1993]:

$$P(R)_i = TAR_i \times P(R \mid A)_i \times L_i \tag{2.9}$$

where:

$P(R)_i$	= probability of an accident involving a dangerous goods release for route segment i
TAR_i	= heavy-vehicle accident rate for route segment i, in units of accidents per vehicle-kilometre
$P(R\|A)_i$	= probability of a dangerous goods release given an accident involving a dangerous goods carrying heavy vehicle for route segment i
L_i	= length of route segment i, in units of kilometres

Ashtakala & Eno [1996] deemed Equation (2.9) suitable for dangerous goods transportation risk analyses because:

- Risk is based on the probability of a dangerous goods release rather than just the probability of an accident.
- Risk is based on heavy-vehicle accident rates rather than all-vehicle accident rates.
- Equation (2.9) retains the proportionality of risk to route segment length.

To illustrate the use of Equations (2.8) and (2.9), Ashtakala & Eno [1996] provided the following example:

Highway class = Multilane divided highway in rural area

Length of road segment = 10 km

Annual Average Daily Traffic volume (AADT) = 3500 vehicles/day

Releasing Accident Rate = 0.118 releases per million vehicle-km [Harwood et al. 1993]

Percentage of heavy vehicles on roadway = 15 % [Harwood et al. 1993]

Average daily heavy-vehicle volume = 0.15 × 3500 = 525 heavy vehicles/day

Vehicle-km on link per year = $525 \times 10 \times 365$ = *1.916 million vehicle-km*

Accident probability = $(1.916 \times 10^{6}) \times (0.118 \times 10^{-6}) = 0.23$

Liquefied Petroleum Gas (LPG) dispersion model:

Fatalities per density exposed to LPG = 0.0015 [Saccomanno et al. 1990]

Population density = *300 persons/km*^{2}

Fatalities per density of 300 persons/km^2 = $300 \times 0.0015 = 0.45$

Risk = Accident probability × Accident consequences

Risk to population = $0.23 \times 0.45 = 0.10$ *fatalities per year*

To establish the accident probability of a road segment, data such as annual average daily traffic (AADT) volume and percentage of heavy vehicles were used. The heavy-vehicle accident rates and releasing accident rates used in the Ashtakala & Eno [1996] study were developed by Harwood et al. [1993] (as discussed in Section 2.4.1). For example, on a multilane divided highway, the dangerous goods releasing accident rate is 0.118 releases per million vehicle-kilometres.

2.9 Transportation Disasters

The United Nations Environment Programme [UNEP, 2001] has compiled details of noteworthy incidents during the transportation of dangerous goods. These incidents are presented in Table 2.8 in chronological order.

Table 2.8: Noteworthy transportation incidents involving dangerous goods [after UNEP, 2001]

Year	Place	Description	Incident Consequences
1974	Eagle Pass, U.S.	Leakage of liquefied petroleum gas (LPG) during road transportation	17 people died, 34 injured
1974	Yokkaichi, Japan	Leakage of Chlorine during a transhipment	521 people injured
1976	Deer Park, U.S.	Accident during road transportation of Ammonia	5 people died, 200 injured
1976	Houston, U.S.	Accident during road transportation of Ammonia	6 people died, 178 injured

Year	Place	Description	Incident Consequences
1978	Los Alfaques, Spain	Tanker delivering Propane to a camp site exploded	216 people died, 200 injured
1978	Youngstown, U.S.	Leakage of Chlorine during rail transportation	8 people died, 138 injured
1979	Suda Bay, Greece	Explosion during transportation of Propane	7 people died, 140 injured
1979	Mississauga, Canada	Train derailment. 3 cars carrying Propane exploded. A Chlorine tank was punctured, releasing Chlorine into the air	250 000 people evacuated from the surrounding area
1981	Montanas, Mexico	Accident during road transportation of Chlorine	28 people died, 1000 injured, 5000 evacuated
1983	Nile River, Egypt	Explosion during transportation of LPG	317 people died, 44 injured
1984	Matamoros, Mexico	Accident during transportation of Ammonia	182 people injured, 3000 evacuated
1987	Annau, USSR	Accident during transportation of Chlorine	200 people injured
1988	Chakhnounia, USSR	Leakage of Pesticides during rail transportation	20 000 people evacuated
1989	Alaska, U.S.	40 million litres of Crude Oil spilled into the ocean from the supertanker Exxon Valdez	Environmental damage. Cleanup cost US$2 billion
1990	Bangkok, Thailand	A tanker carrying LPG crashed, resulting in an explosion	63 people died, 90 injured
1990	Bangkok, Thailand	Accident during transportation of LPG	51 people died, 54 injured
1990	Ahlsfeld, Germany	Release of Chlorine from a heavy vehicle	182 people injured
1991	California, U.S.	Tractor-semitrailer overturned releasing Automotive Gasoline and causing a fire	3 people injured. People in the surrounding area evacuated. Property damage and cleanup costs total US$1 million.
1991	Bombay, India	Accident during transportation of Ammonia Gas	1 person died, 150 injured
1994	Thane District, India	Accident during transportation of Chlorine gas	4 people died, 298 injured
1994	Allentown, U.S.	Explosion and fire in a Natural Gas distribution pipeline	1 person died, 66 injured. Property damage of US$5 million
1994	New York, U.S.	Collision involving Propane heavy vehicle. Tank fractured, releasing Propane and causing a fire.	1 person died, 23 injured. Fire engulfed the area within a radius of 120 metres.
1994	Onitscha, Nigeria	Leakage of Fuel Oil during transportation causing fire	60 people died

Year	Place	Description	Incident Consequences
1994	Palmeira, Mozambique	Gas transportation accident	36 people died
1995	Madras, India	Petroleum transportation accident	100 people died, 23 injured
1995	Mahrashtra, India	Accident during transportation of Ammonia gas	2000 people injured
1996	Alberton, U.S.	A freight train derailed, releasing 59 tons of Chlorine into the air and 64 000 litres of Potassium Hydroxide Solution into the soil	One person died instantly from acute chlorine exposure. 300 area residents who had inhaled chlorine hospitalised. 1000 people evacuated. Over 1000 m^3 of soil contaminated
1996	Lively, U.S.	Pipeline carrying Liquid Butane ruptured. Release followed by a fire.	2 people died, 25 families evacuated. Damage to roadway, properties and adjacent woodlands
1997	Sea of Japan, Japan	Russian oil tanker broke in two, spilling 4.5 million litres of Fuel Oil	Several clean-up workers died, 800 km of coastal land contaminated (including marine life/fisheries) and beaches
1997	Bhopal, India	Ammonia leakage during transportation	400 people injured
1997	Lahore, Pakistan	Accident during transportation of Chlorine	32 people died, 900 injured, 1000 evacuated
1997	Stanger, South Africa	Accident during road transportation of Petroleum	34 people died, 2 injured
1998	Kyrgyzstan	A heavy vehicle transporting Cyanide to a gold mine plunged off a bridge	1800 kg of Sodium Cyanide spilled into a river upstream of several villages. Within days, hundreds of people sought treatment at medical clinics
1998	Idjerhe, Niger Delta, Nigeria	A fire and explosion in a leaking Fuel pipeline	500 people killed. 32 communities affected. Farms and buildings destroyed
1998	Yaundi, Cameroon	Petroleum products transportation accident	220 people died, 130 injured
1998	Biloxi, U.S.	Overflow of Petroleum and subsequent fire at a service station	5 people died, 1 injured. Damages of US$55000
1999	France	8000 tonnes of Fuel Oil escaped from the oil tanker, Erika	100 kilometres of coastline polluted. Seabirds trapped in the oil. The spill had major economic effects on fishing, oyster farming and tourism.
1999	Brand, Austria	Lorry carrying Lacquer crashed into a queue of cars in the Tauertunnel	12 people died, 50 injured. Closure of the tunnel for 3 months, 17 million Deutsche-Marks spent on reconstruction/renovation

Table 2.8 provides compelling evidence that incidents involving the transportation of dangerous goods may have very serious consequences and that there is a need for effective disaster prevention and response planning. The dangerous goods frequently involved in transportation disasters are LPG, Chlorine and Ammonia.

2.10 South African Regulatory Environment

Selected legislation related to the road transportation of dangerous goods is summarised in this section.

Section 27 of the *National Land Transport Transition Bill* [2000] states that transport authorities, core cities and other municipalities must prepare and submit annually to the MEC (member of the Executive Council of a province who is responsible for public transport in the province) integrated transport plans for their respective areas for the coming five-year period. These integrated transport plans must include a general strategy or plan for the movement of dangerous goods by road along designated routes. A person may not transport dangerous goods in the area of a planning authority, except along such a designated route, and any person who does so is guilty of an offence. According to Section 22 of the *National Land Transport Transition Bill* [2000], the MEC, using these integrated transport plans, must annually prepare a provincial land transport framework for the coming five-year period. This provincial land transport framework must set out a general strategy or plan for the movement of dangerous goods by road along designated routes in the province.

The *National Road Traffic Act* [1996] also affects the road transportation of classified dangerous goods and substances. This legislation regulates the transportation of dangerous goods in both bulk and packaged form. Both heavy and light vehicles transporting dangerous goods are required to display the appropriate placarding and to carry the necessary documentation. The legislation contains in excess of 2500 classified dangerous goods. The legislation was summarised by FleetWatch [2001] as follows:

SANS 10228: Identifies and classifies each of the listed dangerous goods and includes information pertinent to the substance including the United Nations number and the correct technical name.

SANS 10229: Includes information on acceptable packaging for dangerous goods and contains requirements for the correct marking, labelling and testing of packages.
SANS 10230: Specifies statutory inspection requirements for all vehicles transporting classified dangerous goods.
SANS 10231: Stipulates operational procedures and rules for transporting dangerous goods and includes the responsibilities of the operator/owner of a dangerous goods vehicle. This code also lists driver qualifications and driver duties before proceeding and while en-route.
SANS 10232 Part 1: Includes placarding requirements for vehicles transporting dangerous goods and compatibility requirements of multiload vehicles.
SANS 10232 Part 3: Includes information on emergency response guides to be used if an incident occurs.
SANS 10233: Contains requirements for Intermediate Bulk Containers and indicates those dangerous goods that may be transported in the intermediate bulk containers.
SANS 1398: Lists design requirements for tankers transporting Petroleum-based flammable substances.
SANS 1518: Stipulates design requirements for normal road tankers transporting dangerous goods and includes the type of materials that may be used in the manufacture of the tankers [FleetWatch, 2001].

In South Africa, the dangerous goods shipment size is primarily constrained by mass limitations such as the 56000-kilogram permissible maximum vehicle mass limit for heavy vehicles [National Road Traffic Act, 1996]. Drivers of heavy vehicles transporting dangerous goods need to obtain a professional driving permit specifically for dangerous goods. To obtain this permit, the driver has to be trained in terms of a minimum syllabus at an approved training body. The driver of a dangerous goods vehicle must carry specific documentation on the vehicle including a transport emergency card for each substance transported, a dangerous goods declaration containing a list of the substances being transported and a clear indication of the route to be taken by the driver [FleetWatch, 2001].

2.11 Local Situation

The *Responsible Care* initiative is the global health, safety and environmental programme initiated by the chemical industry in 1984. It has since been adopted by forty-seven countries. The Chemical and Allied Industries' Association (CAIA) launched

Responsible Care in South Africa in 1994 to respond to public concerns about the manufacture, storage, transport, use and disposal of chemicals. Membership is open to chemical manufacturers as well as to service providers such as storage companies and consultants [CAIA, 2003].

Major chemical companies in South Africa often outsource their transport arrangements. Road accidents involving hauliers carrying dangerous goods are not uncommon on the country's roads. As a result, the CAIA expanded its Responsible Care mandate to include road hauliers involved in the transportation of dangerous goods. The CAIA embarked on a drive to encourage chemical companies to require transporters of their products, to not only become association members, but also Responsible Care signatories [CAIA, 2003]. There are only a few major carriers of dangerous goods in South Africa, dominated by firms that specialize in bulk "liquid" transport, e.g. Tanker Services, Cargo Carriers, Unitrans, etc. [CAIA, 2003].

As at the end of 2002, CAIA had 182 members of whom 104 were signatories to Responsible Care. Companies that have committed to Responsible Care in South Africa account for approximately 90 per-cent of the annual turnover of the chemical manufacturing industry [CAIA, 2003]. The *Responsible Care Performance Report 2002* [CAIA, 2003] stated that over three hundred million tonnes of chemicals were transported by road, rail and pipeline in South Africa in 2002. In this period there were approximately two hundred transportation incidents involving the unintentional release of chemicals. No further breakdown of the proportion of chemicals transported by road or the proportion of road transportation releases was available from the CAIA. This figure of two hundred transportation incidents should be treated as a conservative estimate. Under-reporting of incidents is a serious problem due to the lack of compliance enforcement in the past [Abkowitz et al. 1989].

2.12 Chapter Summary

In this chapter, the literature pertaining to risk assessment of dangerous goods transport was examined. A review was undertaken of the current state of the art and the theory and methodology used by previous researchers. Dangerous goods transportation studies reported in the literature relate to aspects such as risk assessment; database development; designating routes for transporting dangerous goods, etc. Historical records confirm that dangerous goods transportation incidents may have very serious consequences. Dangerous goods releases may occur during normal transport (en-route) or as a result of a traffic accident. Internationally, traffic accidents were found to be the leading cause of severe dangerous goods incidents (deaths, injuries, etc.).

Risk is a measure of relative safety and is defined as a combination of accident likelihood, release probability, consequence of release and risk preference. Risk estimation requires information on: flows of dangerous goods; incidents and accidents; and the population at risk. Accident likelihood is estimated from traffic accident rates and traffic volumes. Estimates of release rates are essential to conduct risk assessments, as an accident involving a dangerous goods vehicle cannot lead to potentially catastrophic consequences unless the cargo is released. The probability of a release, varies with the type of accident and varies between highway classes. Intensive risk analyses should consider the activities of non-residential areas and vulnerable zones (places that concentrate a large amount of people who are difficult to protect or evacuate, e.g. schools, hospitals or commercial centres).

Dispersion modelling may be used to estimate injuries or fatalities resulting from a dangerous goods release. With geographic information systems (GIS), information describing the transportation network, specific chemicals, historical meteorological conditions and population distribution may be combined into an integrated environment. GIS enhances dispersion modelling by allowing consequences and population exposure to be estimated more efficiently. Monte Carlo simulation is a stochastic method for iteratively evaluating a deterministic model using sets of random numbers as inputs. The Monte Carlo simulation approach may be applied to a broad range of problems including the estimation of dangerous goods transportation risks and routing decisions, especially when there are substantial data uncertainties.

The *National Road Traffic Act* [1996] is the principal legislation governing the road transportation of dangerous goods in South Africa. Local legislation stipulates that municipalities and provinces must prepare transport plans for the movement of dangerous goods by road along designated routes.

CHAPTER 3

3. CASE STUDY

This chapter describes the selection of the case study for this investigation. The first step in the risk analysis, the process of hazard identification, is outlined.

3.1 Background

3.1.1 General description of study area

The Durban South Basin, one of South Africa's most important industrial centres, was chosen as the case study for this investigation. Major industry sectors represented in the basin include: automotive components and assembly, food and beverage, petrochemical, pulp and paper, and textile and clothing [CSIR, 1999]. The basin comprises parts of the South Central and South districts of the eThekwini Municipality. Figure 3.1 presents a map of the districts comprising the eThekwini Municipality.

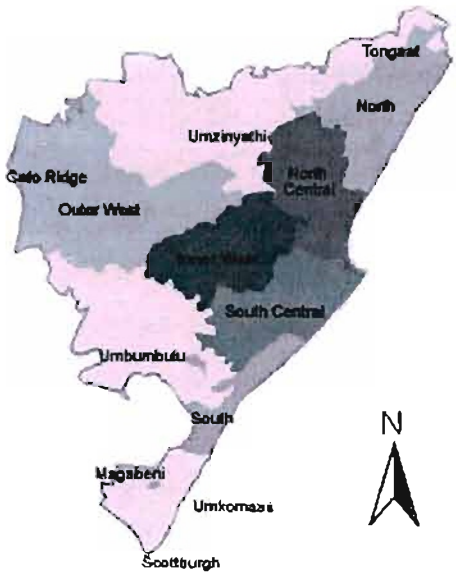


Figure 3.1: Districts of the eThekwini Municipality [eThekwini Municipality GIS, 2005]

The *Durban South Basin Strategic Environmental Assessment* [CSIR, 1999] classified its study area as extending from Umbogintwini in the south to the Durban Bay in the north and extending approximately five kilometres inland of the coast. Figure 3.2 illustrates the extent of the chosen study area.

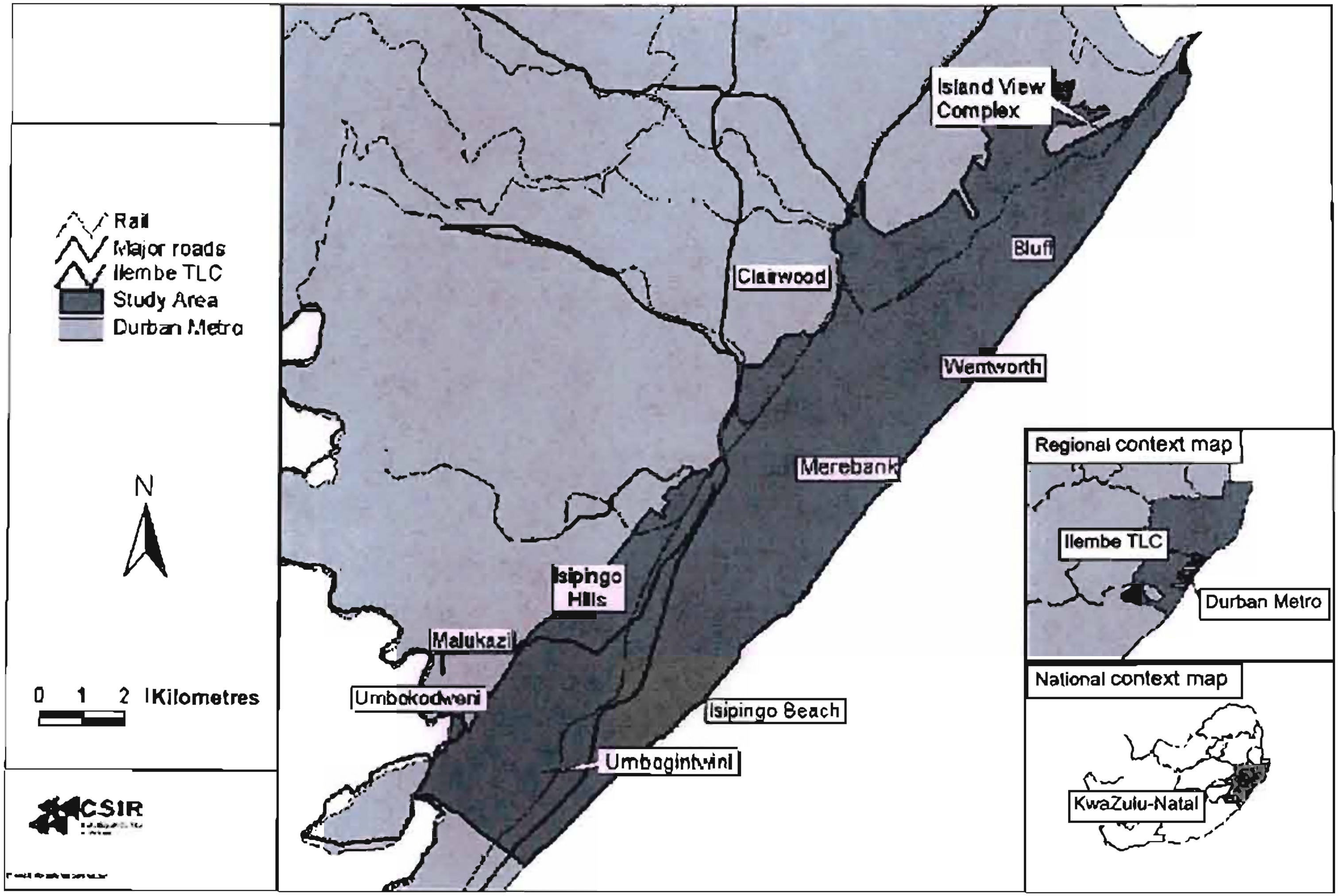


Figure 3.2: The Durban South Basin [CSIR, 1999]

3.1.2 Historical context

Poor development and planning policies in the Durban South Basin have intertwined residential areas (namely Bluff, Clairwood, Isipingo, Merebank, Umlazi and Wentworth) with heavy industry, the Durban International Airport and port infrastructure. Large-scale industrial plants and infrastructure have developed on the floor of the basin. Housing dominates the Bluff dune, valley slopes and ridgelines that surround the Durban South Basin [CSIR, 1999].

Plate 3.1: Communities living in close proximity to industries at Wentworth [Ngeta & Bhikha, 2003]

The wide variety of regions within the Durban South Basin includes:

- The manufacturing and heavy-engineering industrial areas of Jacobs and Mobeni;
- The Clairwood residential zone, which has been the gradually infiltrated by light engineering, manufacturing and transport related industries;
- The industrial zone of Prospecton which houses light industry and manufacturing, including the Toyota South Africa manufacturing plant [CSIR, 1999].

The area directly south of the Durban Harbour is comprised mainly of infrastructure associated with the port. This includes Island View Storage, the largest tank farm in the southern hemisphere. The approximately 1200 tanks are used for bulk liquid storage and warehousing of a range of substances including petrochemicals, jet fuel and toxic chemicals like Acrylonitrile and Benzene [CSIR, 1999]. There are also a number of large industrial complexes in the basin, including:

- The Engen Oil Refinery, which is encircled by the residential areas of Wentworth and Merebank;
- The SAPREF Oil Refinery, which is bounded to the west by the Durban International Airport and to the east by a coastal dune;
- Mondi Paper, which is located north of the Durban International Airport and immediately to the south of Merebank.

3.1.3 Social conditions

The total residential population of the Durban South Basin is approximately 400 000, according to the 1995 Census [Statistics SA Durban Metropolitan Unicity, 2002]. All people within the Durban South Basin are within three kilometres of medical facilities. Austerville, Bluff, Merebank and Wentworth comprise formal housing while Mbokodweni comprises only informal dwellings. There are also informal dwellings in industrial areas surrounding the Durban International Airport and Clairwood [CSIR, 1999].

3.1.4 Traffic and transportation

The Durban South Basin is the main industrial area within the eThekwini Municipality. The eThekwini Municipality Transport Authority has estimated that approximately nineteen thousand vehicles travel into the Durban South Basin every weekday morning during the two-hour peak period (7 AM to 9 AM). By comparison, approximately thirty-six thousand vehicles enter the central Durban area during the morning peak period. High levels of traffic flow occur in the Durban South Basin and significant volumes of dangerous goods, including poisons and flammable liquids are transported between the basin and other destinations within the eThekwini Municipality, and further a-field [CSIR, 1999]. These high flows of dangerous goods, when combined with South Africa's poor road safety record, create numerous opportunities for incidents (including traffic accidents) that could release dangerous goods into the environment and result in public exposure to poisonous, corrosive and possibly carcinogenic substances.

3.2 Approach

It is impossible to conduct a risk assessment for all possible dangerous goods transportation incidents at all possible locations within the basin. Hence, the decision was taken to focus on the dangerous goods being transported to and from the Major Hazard Installations in the Durban South Basin. A Major Hazard Installation (MHI) is an installation where any substance is produced, processed, used, handled or stored in such a form and quantity that it has the potential to cause a major incident. A major incident is defined as an occurrence of catastrophic proportions [Occupational Health and Safety Act, 1993]. MHI's in the Durban South Basin include Island View Storage and the Engen and SAPREF oil refineries. The basis of the decision to focus on MHI's was as follows: if dangerous goods are being stored in sufficient quantities at an installation, such that it is classified as a MHI, then those dangerous goods are being transported to and from said installation (except those dangerous goods that are produced and consumed entirely on site).

The eThekwini Municipality has a Disaster Management Centre. This facility serves as a central point for managing any large-scale emergencies within the city [Mitchell, 2003]. eThekwini Municipality Disaster Management have received Major Hazard Installation risk assessments from approximately sixty MHI's in the Durban South Basin. With the assistance of members of the South Durban Community Environmental Alliance (SDCEA), an environmental non-governmental organisation, and eThekwini Municipality Disaster Management, preliminary locations were identified to begin the hazard identification process of this investigation.

3.3 Preliminary Survey

3.3.1 Selection of appropriate locations for the preliminary survey

The following information regarding dangerous goods traffic within the Durban South Basin, chiefly provided by a member of SDCEA [Ramchurren, 2003], was utilised to select preliminary locations for traffic surveys:

- Island View Storage is located in close proximity to the Fynnland, Ocean View, Grosvenor and Clairwood residential areas. Road tankers leaving Island View proceed down Bayhead Road and then turn into South Coast Road. These tankers then access the M4 Southern Freeway at Exit 4: Edwin Swales VC Drive M7. Edwin Swales VC Drive is also used by tankers to access the N2 at Exit 161 [Ramchurren, 2003].
- Tankers travelling to and from the SAPREF Oil Refinery access the N2 via Exit 149: Prospecton Road and travel through The Avenue East road [Ramchurren, 2003].

A site visit to the area surrounding the Engen Oil Refinery on 22 February 2003 yielded the following information: Tara Road is a two-way, two-lane road that used by tankers travelling to and from Engen. Tankers leaving Engen turn into Duranta Road, which has a steep gradient. Numerous dangerous goods spills have occurred on Duranta Road [Ramchurren, 2003]. These spills have damaged the road, which is slippery in parts and requires resurfacing. During the site visit, it was observed that part of the left lane at the crest of Duranta Road was covered in sand, which had been placed there to cover a recent spill [Ramchurren, 2003].

Anhydrous Hydrogen Fluoride, a highly corrosive and poisonous substance, is transported from Pelindaba, via the N3 to the SAPREF and Engen Oil Refineries [de Klerk, 2004].

Revertex Chemicals on Lansdowne Road, Jacobs is a Major Hazard Installation. The toxic materials handled at Revertex include Acrylonitrile and Vinyl Acetate. Approximately seven Acrylonitrile ISO-tainers are transported to Revertex per annum. This flow is expected to increase to approximately ten Acrylonitrile ISO-tainers with the implementation of the upgrades proposed in Ecoserv [2003]. Raw chemicals are transported to Revertex from Island View and the finished products are transported locally and around South Africa [Ecoserv, 2003].

Based upon the preceding information, the following locations were selected to conduct a preliminary survey:

- The Shell Service Station on Bayhead Road just before the Bayhead Road – South Coast Road intersection. This route is used by heavy goods vehicles travelling to and from the Island View area.
- On Tara Road immediately before the Tara Road – Duranta Road intersection. The Engen Oil Refinery is located on Tara Road.
- Immediately before the entrance to Revertex Chemicals (Pty) Ltd. on Lansdowne Road.
- The Caltex Service Station on The Avenue East just before the Refinery Drive – The Avenue East intersection. This is the predominant route used by heavy goods vehicles travelling to and from the SAPREF Oil Refinery.

3.3.2 Preliminary survey findings

Heavy vehicles transport dangerous goods in bulk inside tanks, containers and ISO-tainers. In addition, light delivery vehicles (LDV's) carry smaller shipments of dangerous goods in drums and cylinders [Ramchurren, 2003]. Vehicles transporting dangerous goods are required by law to display the appropriate hazard label and United Nations (UN) number on the sides of the vehicle. The UN number is allocated to an item of dangerous goods in accordance with the *United Nations Recommendations on the Transport of Dangerous Goods*, which is synonymous with the Substance Identification Number given in SANS 10228 [National Road Traffic Act, 1996]. This UN number is used to identify the dangerous goods being transported when conducting a traffic survey.

A preliminary traffic survey was conducted at the selected locations within the Durban South Basin on Monday, 14 April 2003 and Tuesday, 15 April 2003. The purpose of the preliminary survey was to obtain an indication of: the flows of dangerous goods vehicles, the types of dangerous goods being transported through these locations, the vantage points from which a more extensive survey could be conducted and the number of observers that would be required. A summary of the preliminary survey is presented in Table 3.1.

Table 3.1: Summary of the preliminary survey

Location	Date	Survey period	# of Heavy vehicles passing survey location	# of Dangerous Goods Vehicles passing survey location
Bayhead Road	14/4/2003	8:30-9:30 AM	419	44
Tara Road	14/4/2003	10:40-11:40 AM	27	20
Lansdowne Road	14/4/2003	11:50-12:20 AM	16	3
The Avenue East	15/4/2003	9:10-10:40 AM	90	13
Tara Road	15/4/2003	11:05-12:05 AM	28	21

Dangerous goods are classified according to the type of risk involved [Infosource, 2001]. This system is internationally recognised.

- Class 1: Explosives.
- Class 2: Flammable gases; non-flammable gases, non-toxic gases; toxic gases.
- Class 3: Flammable liquids.

- Class 4: Flammable solids; substances liable to spontaneous combustion; substances that, on contact with water, emit flammable gases.
- Class 5: Oxidizing substances; organic peroxides.
- Class 6: Toxic substances; infectious substances
- Class 7: Radioactive substances
- Class 8: Corrosive substances
- Class 9: Miscellaneous dangerous substances or goods

Dangerous goods are allocated a danger group as follows:

- Danger group I: substances that present a very severe risk
- Danger group II: substances that present a serious risk
- Danger group III: substances that present a relatively low risk
- Danger group IV: substances that present a very low risk [Infosource, 2001]

Table 3.2 presents a selection of the dangerous goods identified during the preliminary survey, including substances belonging to Danger groups I and II. A full listing of the dangerous goods identified during the preliminary survey is presented in Appendix A.

Table 3.2: Selected dangerous goods identified during the preliminary survey

UN No.	Dangerous Goods	Class	Danger Group	Location			
				Tara Road	The Avenue East	Bayhead Road	Lansdowne Road
1075	Liquefied Petroleum Gases	2	-		√		
1090	Acetone	3	II			√	
1114	Benzene	3	I	√	√		
1203	Petrol	3	II	√	√	√	
1230	Methanol	3	II			√	
1245	Methyl Isobutyl Ketone	3	II			√	
1247	Methyl Methacrylate Monomer	3	II			√	
1294	Toluene	3	II			√	
1547	Aniline	6	II			√	
1649	Tetra Ethyl Lead	6	I		√		
2078	Toluene Diisocyanate	6	II			√	

Ecoserv [2003] disclosed the following information about Revertex Chemicals: Acrylonitrile and other dangerous goods (including Caustic Soda and Ammonia) are transported to Revertex from the Cutler Complex at Island View by the transport company Cargo Carriers. Approximately 50 per-cent of products are transported from the Revertex site by bulk road tanker, with much of the remainder being transported via

210 litre drums and one-ton mini bulk containers. Dangerous goods are delivered to site from Monday to Friday during normal daytime working hours. On average, one bulk road tanker per day is delivered to Revertex. The route used by Cargo Carriers to transport dangerous goods to Revertex from Island View includes the Bayhead Road – South Coast Road and Edwin Swales VC Drive – South Coast Road intersections [Ecoserv, 2003]. Due to the comparatively low volume of dangerous goods vehicles observed during the survey on Lansdowne Road, the decision was taken to exclude Revertex Chemicals from further direct investigation. However, vehicles travelling to and from Revertex would contribute to the dangerous goods flows at the Bayhead Road – South Coast Road and Edwin Swales VC Drive – South Coast Road intersections.

Nalco Chemserve, which manufactures speciality chemicals, is part of the AECI Industrial Complex at Umbogintwini, located approximately twenty-two kilometres south of Durban. The dangerous goods handled at Nalco Chemserve include: Acrylonitrile, Epichlorohydrin and Hydrochloric Acid [Mitchell, 2003]. A survey on Moss Kolnik Road outside the south gate of the AECI Industrial Complex site was attempted. However, this survey was abandoned due to safety concerns.

3.4 Intersection Surveys

3.4.1 Accidents and intersections

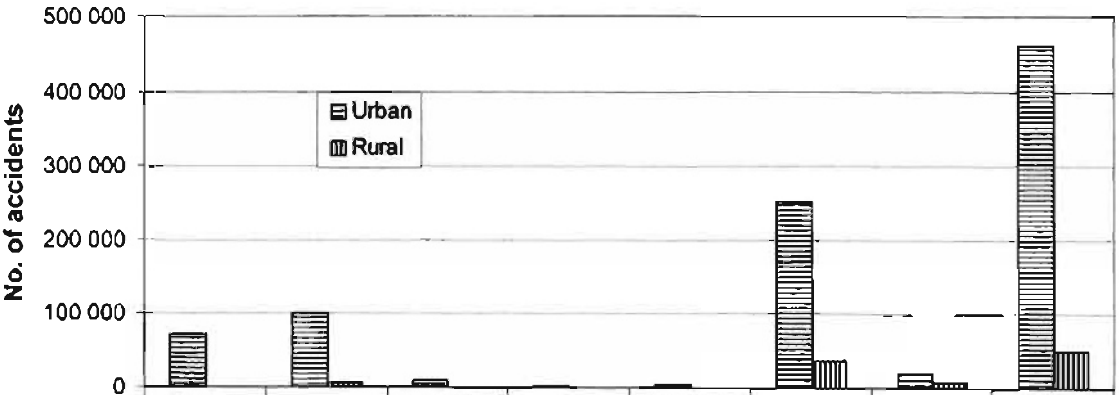
Dangerous goods producers and customers are generally well prepared to deal with incidents. However, if dangerous goods releases were to occur during transportation, they would be more problematic because the emergency response is usually handled by local authorities (fire departments and police) who would have less experience with these substances [Pet-Armacost et al. 1999]. As discussed in Section 2.1.3, traffic accidents are the leading cause of severe dangerous goods incidents (i.e. deaths, injuries, etc) [Harwood & Russell, 1989; Saccomanno & Shortreed, 1993]. Hence, the decision was taken to focus this investigation on accident-related releases of dangerous goods.

Furthermore, in comparison to developed countries, South Africa's road safety record is very poor. Table 3.3 illustrates that South Africa's road fatality rate per 100 000 vehicles is over eight times the level of that in Australia, the U.S. and Canada.

Table 3.3: Comparison of South Africa's road fatality rates with those of developed countries [after Road Accident Fund Commission, 2002]

Country	Road fatalities per 100 000 population	Road fatalities per 100 000 vehicles
Australia	12.09	21.62
Canada	13.81	21.51
U.S.	16.35	21.53
South Africa	31.78	181.83

Figure 3.3 illustrates that in South Africa, in 1998; the majority of road accidents occurred in urban areas (90 per-cent). The highest number of accidents occurred on straight roads, followed by stop/yield locations (i.e. unsignalised intersections) and traffic signals (i.e. signalised intersections). When the analysis is limited to urban areas, accidents at intersections account for approximately 37 per-cent of the total number of urban accidents [Road Accident Fund Commission, 2002].



	Traffic signal	Stop/ yield	Pedestrian Crossing	Rail	Freeway Ramp	Straight road	Curved road	Total
Urban	71 843	100 739	10 418	993	3 915	252 821	20 098	460 827
Rural	646	5 002	762	88	486	36 381	7 413	50 778

Figure 3.3: Locations at which accidents occurred, South Africa, 1998 [after Road Accident Fund Commission, 2002]

Accidents at intersections tend to be more serious than those on road segments [Vogt, 1999]. Studies in other countries confirm that a high percentage of accidents occur at intersections. Hakkert & Mahalel [1978] observed that more than 50 per-cent of accidents in Israel occur at intersections. The study included both injury and fatality accidents, on two-lane and four-lane roads, at signalised and unsignalised intersections. Pickering, Hall & Grimmer [1986], in a study of UK data from 1983, reported that one-third of injury accidents occurred at intersections. Yinhai, Hitoshi & Mannering [2003] found that in Japan, approximately 60 per-cent off all accidents and 45 per-cent of fatal accidents occur at intersections.

The prevalence of accidents at intersections can be partially attributed to the conflicting manoeuvres undertaken by vehicles [Hauer, Ng & Lovell, 1988; Roebuck, 2003]. Figure 3.4 illustrates a frequent accident pattern at intersections: two vehicles from different approaches are attempting conflicting manoeuvres during a green phase at a signalised intersection that has simple phasing (i.e. no indicative green arrow for right-turning vehicles). The term *phase* is used to describe a set of traffic manoeuvres that can occur simultaneously, or the sequence of traffic signal indications received by such a set of manoeuvres [Cannell & Gardner, 1996].

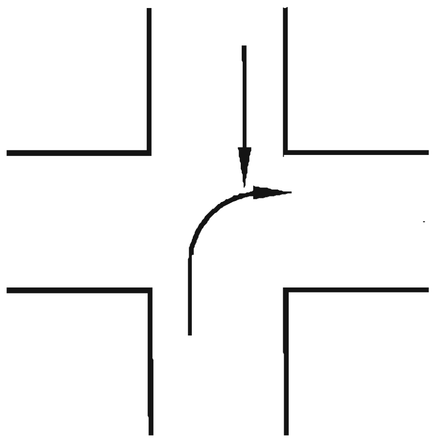


Figure 3.4: Common conflicting manoeuvres at a signalised intersection [after Hauer et al. 1988]

Vogt [1999] reported that signalised intersections that had a higher percentage of heavy-vehicle traffic on any or all approaches, compared to other signalised intersections, showed a rise in the number of accidents. Heavy vehicles at a signalised intersection, in addition to having greater destructive capacity than passenger vehicles, take a longer time to engage in turning manoeuvres (hence, occupying the collision zone for a longer period) and block visibility during this time [Vogt, 1999].

Based upon the preceding information, the decision was taken to focus this investigation on intersections, where there is a greater possibility of a dangerous goods carrying vehicle being involved in an accident.

3.4.2 Use of historical accident data to select intersections

It was necessary to select appropriate intersections in urban areas. The following criteria were utilised to appraise intersections as possible data sources:

- Proximity to dangerous goods trip generators, e.g. Major Hazard Installations
- Historical accident record

The historical accident records of Durban South Basin intersections in close proximity to MHI's were obtained from the eThekwini Municipality Transport Authority. The most recent three-year records are presented in Table 3.4.

Table 3.4: Accident records of selected intersections, 2000-2002

Intersection	Total Accidents (all vehicle types)			
	2000	2001	2002	Mean
South Coast Road - M7 Edwin Swales VC Drive	**224**	**226**	**186**	**212**
N2 - M7 Edwin Swales VC Drive (East)	56	63	61	60
N2 - M7 Edwin Swales VC Drive (West)	54	61	53	56
Bayhead Road - South Coast Road	**70**	**39**	**58**	**56**
R102 Prospecton Road - The Avenue East	24	31	42	32
R102 Prospecton Road - N2 (East)	32	25	29	29
R102 Prospecton Road - N2 (West)	8	14	15	12
M4 Southern Freeway - Duranta Road (East)	**13**	**13**	**26**	**17**
M4 Southern Freeway - Duranta Road (West)	**6**	**16**	**16**	**13**
The Avenue East - Refinery Drive	**17**	**13**	**14**	**15**
Tara Road - Duranta Road	**12**	**12**	**9**	**11**
Joyner Road - N2 (East)	13	7	9	10
Joyner Road - N2 (West)	3	8	5	5

The intersections highlighted in **bold text** in Table 3.4 were selected for further study due to: the findings of the preliminary survey, their historical accident record and their close proximity to dangerous goods trip generators, specifically:

- Engen Oil Refinery (Tara Road - Duranta Road, M4 Southern Freeway - Duranta Road (East) and M4 Southern Freeway - Duranta Road (West) intersections)
- SAPREF Oil Refinery (The Avenue East - Refinery Drive intersection)
- Island View Storage (Bayhead Road - South Coast Road and South Coast Road - Edwin Swales VC Drive intersections)

Large heavy vehicles appear to experience particular problems at interchange ramps, where high rates of acceleration and deceleration occur. Harwood & Russell [1989], studying fatal accidents in the U.S., reported that in comparison to other locations, off-ramps at freeway interchanges had the highest proportion of *overturned heavy-vehicle* *accidents*. These findings provided further motivation to include the M4 Southern Freeway - Duranta Road (East) and M4 Southern Freeway - Duranta Road (West) intersections.

3.4.3 Dangerous goods surveys at selected intersections

Traffic surveys were conducted at the following intersections: Bayhead Road – South Coast Road; Edwin Swales VC Drive – South Coast Road; Tara Road – Duranta Road; M4 Southern Freeway – Duranta Road; and The Avenue East – Refinery Drive. The parameters recorded in the surveys included the:

- UN number of the dangerous goods being transported;
- Direction of approach and type of manoeuvre at intersection (e.g. From North turning right, etc);
- Vehicle configuration (e.g. Light delivery vehicle or LDV, Single-unit heavy goods vehicle, articulated heavy vehicle, multiple-articulated heavy vehicle);
- Load configuration (e.g. tank, container, drums, cylinders)

The survey data were broken down into fifteen-minute counts.

In order to avoid double-counting during the survey and to avoid confusion during the subsequent analysis in later chapters, the M4 Southern Freeway - Duranta Road (East) and M4 Southern Freeway - Duranta Road (West) intersections were treated as a single intersection and designated the *M4 Southern Freeway - Duranta Road intersection.*

Roebuck [2003] suggested a six-hour observation period at each intersection in order to collect the necessary data, with the observation periods divided into one-hour segments covering various days where possible. The one-hour segments are recommended to cater for variations in traffic flow that might occur. Table 3.5 presents a summary of the surveys conducted at the five intersections. Appendix B contains a complete listing of the dates and times of each intersection survey, the specific dangerous goods identified, and directional dangerous goods vehicle traffic volumes.

Table 3.5: Summary of six-hour dangerous goods intersection surveys

Intersection	# of Dangerous Goods Vehicles	# of Dangerous Goods Heavy Vehicles (excluding LDV's)
Bayhead Road – South Coast Road	288	241
Edwin Swales VC Drive – South Coast Road	340	328
M4 Southern Freeway – Duranta Road	148	141
Tara Road – Duranta Road	172	167
The Avenue East – Refinery Drive	89	57

SAPREF Oil Refinery's fuel decanting depot is situated at Island View Storage, which is linked to SAPREF by pipeline. This may account for the comparatively lower volume of dangerous goods vehicles recorded at The Avenue East – Refinery Drive intersection. On average fifty road tankers are serviced and loaded per twenty-four hours at this fuel-decanting depot. However, LPG is decanted into road tankers at the SAPREF Oil Refinery itself [Badstübner, 2003]. Hence, fuel produced at SAPREF contributes to the dangerous goods flows at the Bayhead Road – South Coast Road and Edwin Swales VC Drive – South Coast Road intersections.

The details of *all* vehicles transporting dangerous goods were recorded during the surveys. It was noted that light delivery vehicles (LDV's) carry smaller shipments of dangerous goods in drums and cylinders. Heavy vehicles transport dangerous goods in bulk inside tanks, containers and ISO-tainers. Hence, the decision was taken to focus this investigation on heavy vehicles transporting dangerous goods. Accidents involving heavy vehicles may have far more serious consequences, due to the larger quantities of dangerous goods involved.

Three different heavy-vehicle configurations are of interest to dangerous goods transportation. These are: single-unit heavy vehicles; articulated heavy vehicles; and multiple-articulated heavy vehicles. Articulated heavy vehicles consist of a separate tractor and single semi-trailer unit joined with a trailer hitch. Multiple articulated heavy vehicles consist of a tractor pulling a semi-trailer followed by a full trailer [Harwood & Russell, 1989].

3.4.4 Chemical identification at intersections

The dangerous goods belonging to Danger group I, identified during the surveys, are presented in Table 3.6. Appendix B contains a complete listing of the dangerous goods identified at each intersection during the surveys.

Table 3.6: Dangerous goods allocated to Danger group I, identified during the surveys

				Intersection				
UN No.	**Dangerous Goods**	**Class**	**Danger Group**	**Tara Road – Duranta Road**	**M4 Southern Freeway – Duranta Road**	**The Avenue East – Refinery Drive**	**Bayhead Road – South Coast Road**	**Edwin Swales VC Drive – South Coast Road**
1093	Acrylonitrile	6.1	I				√	
1114	Benzene	3	I	√	√	P†	√	
1221	Isopropylamine	3	I				√	√
1649	Tetra Ethyl Lead	6.1	I	√		P	√	√
2902	Methyl Isocyanate*	6.1	I/II/III	√	√			

†These dangerous goods were recorded during the preliminary survey but not during the full six-hour survey.

*The *Dangerous Goods Standard Source* [Infosource, 2001] identifies UN number 2902 as "Pesticides, liquid, toxic". This record represents many different insecticide compounds. However, the words "Methyl Isocyanate" were clearly displayed on these tankers recorded during the traffic surveys. Yet, the correct UN number for Methyl Isocyanate is 2480. This raises concerns that some hauliers are transporting dangerous goods without displaying the correct chemical signage boards. The correct boards indicate how each product is to be dealt with in an emergency. Hence, emergency workers are being placed at risk, as specific chemicals require specific responses.

Anhydrous Hydrogen Fluoride, a highly corrosive and poisonous substance allocated to Danger group I, is transported via the N3 to the SAPREF Oil Refinery (sixteen tons monthly) and Engen Oil Refinery (six tons monthly) [de Klerk, 2004]. Hence, Anhydrous Hydrogen Fluoride is transported through the: Tara Road – Duranta Road; M4 Southern Freeway – Duranta Road; and The Avenue East – Refinery Drive intersections.

As described in Section 3.3, up to ten Acrylonitrile ISO-tainers per annum are transported to Revertex through the Bayhead Road – South Coast Road and Edwin Swales VC Drive – South Coast Road intersections [Ecoserv, 2003].

Combining this information with Table 3.6, yields Table 3.7 which contains an expanded listing of the dangerous goods belonging to Danger group I, that are being transported through the selected intersections.

Table 3.7: Dangerous goods allocated to Danger group I, transported through selected intersections

				Intersection				
UN No.	**Dangerous Goods**	**Class**	**Danger Group**	**Tara Road – Duranta Road**	**M4 Southern Freeway – Duranta Road**	**The Avenue East – Refinery Drive**	**Bayhead Road – South Coast Road**	**Edwin Swales VC Drive – South Coast Road**
1052	Anhydrous Hydrogen Fluoride	8	I	√	√	√		
1093	Acrylonitrile	6.1	I				√	√
1114	Benzene	3	I	√	√	√	√	
1221	Isopropylamine	3	I				√	√
1649	Tetra Ethyl Lead	6.1	I	√		√	√	√
2902	Methyl Isocyanate	6.1	I/II/III	√	√			

3.5 Chapter Summary

The Durban South Basin, one of South Africa's most important industrial centres, was chosen as the case study for this investigation. High levels of traffic flow occur in the Durban South Basin and significant volumes of dangerous goods are transported on the roads of the basin daily. These high flows of dangerous goods, when combined with South Africa's poor road safety record, create numerous opportunities for incidents (including traffic accidents) that could release dangerous goods into the environment and result in public exposure to poisonous, corrosive and possibly carcinogenic substances.

The decision was taken to focus on the dangerous goods being transported to and from the Major Hazard Installations in the Durban South Basin, including Island View

Storage and the Engen and SAPREF oil refineries. Preliminary surveys were conducted at selected locations within the basin in order to obtain an indication of: the flows of dangerous goods vehicles, the types of dangerous goods being transported through these locations, the vantage points and manpower requirements for a more extensive survey.

Traffic accidents are the leading cause of severe dangerous goods incidents (i.e. deaths, injuries, etc). In South Africa, the majority of road accidents occur in urban areas and accidents at intersections account for a high percentage of the total number of urban accidents. Accidents at intersections tend to be more serious than those on road segments. Dangerous goods accidents involving heavy vehicles may have far more severe consequences than those involving light delivery vehicles, due to the larger quantities of dangerous goods involved. Hence, the decision was taken to focus this investigation on intersections, where there is a greater possibility of a heavy-vehicle transporting dangerous goods being involved in an accident.

Traffic surveys were conducted at the following intersections: Bayhead Road – South Coast Road; Edwin Swales VC Drive – South Coast Road; Tara Road – Duranta Road; M4 Southern Freeway – Duranta Road; and The Avenue East – Refinery Drive. These intersections were chosen for study based on: the findings of the preliminary survey, their historical accident records and their proximity to dangerous goods trip generators such as Major Hazard Installations. Analysis of the traffic surveys yielded the specific dangerous goods being transported and directional dangerous goods vehicle flows at the selected intersections. Combining information obtained from a desk study with the analysis of the traffic surveys, yielded a listing of the dangerous goods, belonging to Danger group I (substances that present a very severe risk), that are being transported through the chosen intersections: Acrylonitrile, Anhydrous Hydrogen Fluoride, Benzene, Isopropylamine, Methyl Isocyanate and Tetra Ethyl Lead.

CHAPTER 4

4. LIKELIHOOD OF DANGEROUS GOODS ACCIDENTS AND RELEASES

This chapter describes the methodology developed to estimate dangerous goods accident and release rates at intersections. Two approaches are utilised, a deterministic model and Monte Carlo simulation.

The technique that has been developed to estimate dangerous goods accident and release rates is summarised by the following relationships:

$$\begin{aligned}&\textit{Dangerous Goods Accident Rate}\\&= \textit{Heavy Vehicle Accident Rate} \times\\&\quad \textit{Proportion of Heavy vehicles transporting Dangerous Goods}\end{aligned} \tag{4.1}$$

$$\begin{aligned}&\textit{Dangerous Goods Releasing Accident Rate}\\&= \textit{Dangerous Goods Accident Rate} \times\\&\quad \textit{Probability of release} \mid \textit{Dangerous Goods accident}\end{aligned} \tag{4.2}$$

where: the symbol " | " means "given". As discussed in Section 3.4.3, the decision was taken to focus this investigation on heavy vehicles transporting dangerous goods. Accidents involving heavy vehicles may have far more serious consequences, due to the larger quantities of dangerous goods involved.

4.1 Deterministic Model for Dangerous Goods Accidents

A review of the literature did not reveal any dangerous goods transportation studies specifically focussing on intersections. Nevertheless, the principles of the research cited in Chapter 2 (notably the development of dangerous goods heavy-vehicle accident and release rates for route segments by Harwood et al. [1993]) were utilised and adapted for use in this investigation.

The development and implementation of the deterministic approach used to estimate dangerous goods accident and release rates at intersections, is detailed in this section. The Edwin Swales VC Drive – South Coast Road intersection is used as an example. Spreadsheets were used to perform the calculations in this investigation. Hence, the parameters were calculated to a greater number of significant figures than shown in the text.

4.1.1 Heavy-vehicle accident rate

The first step in estimating the dangerous goods accident and release rates was the estimation of the *Heavy-vehicle Accident Rate*. Accident studies require the use of three years of historical data in order to perform adequate statistical analysis [FHWA, 1994; Roebuck, 1989; Roebuck, 2003]. If available, a longer historical record may be used to increase the precision of the analysis. The most recent three-year record of heavy-vehicle accidents was obtained from the eThekwini Municipality Transport Authority for each of the intersections selected for survey. From 1 January 2000 to 31 December 2002, there were 297 heavy-vehicle accidents at the Edwin Swales VC Drive – South Coast Road intersection. Hence, the heavy-vehicle accident rate may be estimated as:

$$\textit{Heavy-vehicle Accident Rate} = \frac{\textit{Heavy-vehicle accidents in 3 years}}{3}$$
$$= \frac{297}{3} = 99 \textit{ Heavy-vehicle accidents/year} \qquad (4.3)$$

The assumption was made that only one heavy vehicle was involved in each reported heavy-vehicle accident. Therefore, there were 297 heavy vehicles involved in accidents at the Edwin Swales VC Drive – South Coast Road intersection during 2000-2002. This is a reasonable assumption as most heavy-vehicle accidents are with passenger cars [Harwood & Russell, 1989; Hauer, 2001]. The necessity of this assumption is discussed in Section 4.1.3. Hence, at the Edwin Swales VC Drive – South Coast Road intersection:

$$\textit{Heavy-vehicle Accident Rate} = 99 \textit{ Heavy vehicles involved in accidents/year}$$

4.1.2 Exposure

Exposure may be regarded as the opportunity for accident involvement. The purpose of measuring exposure is to enable a reasonable assessment of accident risk to be made. Intersection exposure may be measured by the volume of vehicles entering a given intersection over a specific period of time, usually one year [Khanabis & Assar, 1989].

The eThekwini Municipality conducts manual counts of traffic volumes at intersections within the metropolitan area. Twelve-hour counts of traffic volumes are undertaken, usually between 6 AM and 6 PM on a weekday. The traffic volumes are recorded in fifteen-minute sub-totals and categorised into vehicle-type (e.g. car, bus, heavy vehicle), direction of approach (e.g. North, South, etc.) and type of manoeuvre (e.g. proceeding straight, turning left or right). When necessary, usually after a period of a few years, these counts are repeated. Traffic volumes for the selected intersections were provided by the eThekwini Municipality Transport Authority for use in this investigation.

A total volume of 8985 heavy vehicles entered the Edwin Swales VC Drive – South Coast Road intersection between 6 AM and 6 PM during the eThekwini Municipality traffic count on 22 April 2002.

A procedure developed to expand this twelve-hour weekday count into an *Annual Traffic Volume*, taking into consideration after-hours and weekend traffic, is detailed in Appendix C. This procedure yields:

$$\textit{Annual Traffic Volume} = 3.44 \times 10^6 \textit{ Entering Heavy vehicles/year}$$

4.1.3 Probability of heavy-vehicle accident

Using the historical accident record and the estimated exposure, the probability of a heavy-vehicle accident may be estimated as:

$$\begin{aligned} &\textit{Probability of Heavy-vehicle Accident} = \frac{\textit{Heavy-vehicle Accident Rate}}{\textit{Annual Traffic Volume}} \\ &= \frac{99 \textit{ Heavy vehicles involved in accidents/year}}{3.44 \times 10^6 \textit{ Heavy vehicles/year}} = 2.88 \times 10^{-5} \end{aligned} \tag{4.4}$$

The reasoning behind expressing the *Heavy-vehicle Accident Rate* in terms of *Heavy vehicles involved in accidents/year* is clarified in Equation (4.4). Probabilities are dimensionless, and since the denominator is the exposure of *vehicles*, the numerator should also be the count of *vehicles*, not the count of *accidents*. The use of this approach is based upon the recommendations of Hauer [2001].

4.1.4 Proportion of heavy vehicles transporting dangerous goods

Only the details of dangerous goods vehicles were recorded during the six-hour intersection surveys conducted as part of this investigation. Recording the flows and manoeuvres of *all* heavy vehicles entering the surveyed intersections would have increased the number of observers required to conduct the surveys. Hence, the heavy-vehicle traffic volumes needed to be estimated from the eThekwini Municipality traffic counts.

A total volume of 328 heavy vehicles transporting dangerous goods was recorded during the six-hour dangerous goods survey at the Edwin Swales VC Drive – South Coast Road intersection.

A total volume of 4905 Heavy vehicles entered the Edwin Swales VC Drive – South Coast Road intersection during the same six hours of the eThekwini Municipality traffic count on 22 April 2002.

Hence, the proportion of heavy vehicles transporting dangerous goods may be estimated as:

$$\begin{aligned} &\text{Proportion of Heavy vehicles transporting Dangerous Goods} \\ &= \frac{\text{\# of Heavy vehicles transporting Dangerous Goods}}{\text{Estimated \# of Heavy vehicles}} \\ &= \frac{328}{4905} \\ &= 0.0669 \text{ Dangerous Goods Heavy vehicles/Entering Heavy vehicle} \end{aligned} \tag{4.5}$$

4.1.5 Dangerous goods accident rate

The assumption was made that heavy vehicles transporting dangerous goods, are just as likely to be involved in an accident, as other heavy vehicles. Hence, the number of dangerous goods accidents per entering heavy vehicle, may be estimated as:

$$
\begin{aligned}
&\textit{Dangerous Goods accidents/Entering Heavy vehicle}\\
&= \textit{Probability of Heavy-vehicle accident} \times\\
&\quad \textit{Proportion of heavy vehicles transporting dangerous goods}\\
&= \left(2.88 \times 10^{-5}\right) \times 0.0669 \qquad (4.6)\\
&= 1.92 \times 10^{-6} \textit{ Dangerous Goods Heavy vehicles involved in accidents/Entering Heavy vehicle}\\
&= 1.92 \times 10^{-6} \textit{ Dangerous Goods accidents/Entering Heavy vehicle}^{*}
\end{aligned}
$$

*Based on the assumption introduced in Section 4.1.1 that one dangerous goods heavy vehicle is involved in each dangerous goods accident.

The number of entering heavy vehicles per dangerous goods accident may be estimated by taking the inverse of Equation (4.6):

$$
\begin{aligned}
&\textit{Entering Heavy vehicles/Dangerous Goods accident}\\
&= 1/\left(\textit{Dangerous Goods accidents/Entering Heavy vehicle}\right)\\
&= 1/1.92 \times 10^{-6} \qquad (4.7)\\
&= 5.20 \times 10^{5} \textit{ Entering Heavy vehicles/Dangerous Goods accident}
\end{aligned}
$$

Thus, by including the estimated exposure, the recurrence interval for dangerous goods accidents may be estimated as:

$$
\begin{aligned}
&\textit{Years/Dangerous Goods accident}\\
&= \frac{\textit{Entering Heavy vehicles/Dangerous Goods accident}}{\textit{Entering Heavy vehicles/year}}\\
&= \frac{5.20 \times 10^{5}}{3.44 \times 10^{6}} = 0.151 \textit{ Years/Dangerous Goods accident} \qquad (4.8)
\end{aligned}
$$

The *Dangerous Goods Accident Rate* may be estimated as:

$$
\begin{aligned}
&\textit{Dangerous Goods Accident Rate}\\
&= \textit{Dangerous Goods accidents/Entering Heavy vehicle} \times\\
&\quad \textit{Entering Heavy vehicles/year}\\
&= 1.92 \times 10^{-6} \times 3.44 \times 10^{6} \qquad (4.9)\\
&= 6.62 \textit{ Dangerous Goods accidents/year}\\
&\equiv 1/\left(\textit{Years/Dangerous Goods accident}\right)
\end{aligned}
$$

The *Dangerous Goods Accident Rate* may also be estimated by taking the inverse of Equation (4.8).

4.1.6 Probability of release

The U.S. Federal Highway Administration (FHWA) Office of Motor Carriers maintains a database of heavy-vehicle accident reports. Studying this database, Harwood & Russell [1989] derived Table 4.1. For the period 1984-1985, Table 4.1 presents the distribution of accidents involving dangerous goods carrying heavy vehicles by their relationship to intersections, freeway ramps and railway-highway grade crossings.

Table 4.1: Distribution of FHWA-reported heavy-vehicle accidents by relationship to intersecting facility, 1984-1985 [Harwood & Russell, 1989]

Relationship to intersecting facility	Non-dangerous goods heavy-vehicle accidents		Dangerous goods heavy-vehicle accidents				
			Combined		No release	Release	Release Probability
	No.	%	No.	%	No.	No.	
None	60 828	85.5%	3 172	85.7%	2 726	446	14.1%
At-grade intersection	5 762	8.1%	283	7.6%	273	10	3.5%
Off-ramp	2 376	3.3%	116	3.1%	86	30	25.9%
On-ramp	1 884	2.6%	110	3.0%	86	24	21.8%
Railway grade crossing	314	0.4%	22	0.6%	12	10	45.5%
Total	71 164	100%	3 703	100%	3 183	520	14.0%

Heavy-vehicle at-grade intersection accidents appear to be less likely to result in a dangerous goods release (3.5 per-cent probability), compared to the 14 per-cent of all accidents involving dangerous goods carrying heavy vehicles that result in a release.

The probability of a release, given that an accident involving a dangerous goods vehicle has occurred, also varies with the type of accident. The release probabilities presented in Table 4.2 were developed by Harwood & Russell [1989] using information reported to the U.S. FHWA for the period 1984-1985.

Table 4.2: Probability of release as function of accident type, given an accident involving a dangerous goods carrying heavy vehicle [Harwood & Russell, 1989]

	Accident type	Probability of a release given a dangerous goods accident
Single-vehicle non-collision accidents	Run-off-road	33.1%
	Overturned (in road)	37.5%
	Other non-collision	16.9%
Single-vehicle collision accidents	Collision with parked vehicle	3.1%
	Collision with train	45.5%
	Collision with non-motorist	1.5%
	Collision with fixed object	12.9%
	Other collision	5.9%
Multiple-vehicle collision accidents	Collision with passenger car	3.5%
	Collision with heavy vehicle	9.4%
	Collision with other vehicle	3.7%

Multiple-vehicle collisions were reported to be the leading type of accident for both heavy vehicles carrying and not carrying dangerous goods. However, the leading accident types that resulted in a dangerous goods release were single-vehicle overturning accidents and single-vehicle run-off-road accidents. Accidents at intersections typically involve multiple-vehicle collisions. U.S. FHWA historical data indicated that multiple-vehicle collisions were less likely to result in a dangerous goods release [Harwood & Russell, 1989].

Unfortunately, no South African dangerous goods statistics were available to estimate the probability of release given an accident involving a dangerous goods vehicle. Hence, based on the information presented in Table 4.1:

$$\textit{Probability of release} \mid \textit{Dangerous Goods accident} = 0.140$$

where: the symbol " | " means "given". Hence, the assumption was made that a heavy vehicle transporting dangerous goods has a 14 per-cent probability of releasing its cargo, if it is involved in an accident. The decision was taken to use the release probability value presented in Table 4.1 for *all* accidents involving heavy vehicles transporting dangerous goods, not the value for *at-grade intersection accidents*, because of the larger sample size used to estimate the former.

4.1.7 Dangerous goods releasing accident rate

A *releasing* dangerous goods accident occurs when a heavy vehicle transporting dangerous goods is involved in an accident, and a fraction of the cargo is released. The number of releasing dangerous goods accidents per entering heavy vehicle, may be estimated as:

$$\begin{aligned}&\textit{Releasing Dangerous Goods accidents/Entering Heavy vehicle}\\&= \textit{Dangerous Goods accidents/Entering Heavy vehicle} \times\\&\quad \textit{Probability of release} \mid \textit{Dangerous Goods accident}\\&= \left(1.92 \times 10^{-6}\right) \times 0.140\\&= 2.70 \times 10^{-7}\ \textit{Releasing Dangerous Goods accidents/Entering Heavy vehicle}\end{aligned} \tag{4.10}$$

Taking the inverse of Equation (4.10), the number of entering heavy vehicles per releasing dangerous goods accident, may be estimated as:

$$\begin{aligned}&\textit{Entering Heavy vehicles/Releasing Dangerous Goods accident}\\&= 1 \big/ \left(\textit{Releasing Dangerous Goods accidents/Entering Heavy vehicle}\right)\\&= 1 \big/ 2.70 \times 10^{-7}\\&= 3.70 \times 10^{6}\ \textit{Entering Heavy vehicles/Releasing Dangerous Goods accident}\end{aligned} \tag{4.11}$$

Thus, the recurrence interval for releasing dangerous goods accidents may be estimated as:

$$\begin{aligned}&\textit{Years/Releasing Dangerous Goods accident}\\&= \frac{\textit{Entering Heavy vehicles/Releasing Dangerous Goods accident}}{\textit{Entering Heavy vehicles/year}}\\&= \frac{3.70 \times 10^{6}}{3.44 \times 10^{6}}\\&= 1.08\ \textit{Years/Releasing Dangerous Goods accident}\end{aligned} \tag{4.12}$$

Hence, taking the inverse of Equation (4.12), the *Dangerous Goods Releasing Accident Rate* may be estimated as:

$$\begin{aligned}&\textit{Dangerous Goods Releasing Accident Rate}\\&= \frac{1}{(\textit{Years/Releasing Dangerous Goods accident})}\\&= \frac{1}{1.08}\\&= 0.93 \textit{ Releasing Dangerous Goods accidents/year}\end{aligned} \tag{4.13}$$

4.1.8 Application of deterministic approach to other intersections

Using the deterministic approach outlined in Sections 4.1.1 to 4.1.7, the dangerous goods accident and release rates have been estimated at the Bayhead Road – South Coast Road; Edwin Swales VC Drive – South Coast Road; Tara Road – Duranta Road; M4 Southern Freeway – Duranta Road; and The Avenue East – Refinery Drive intersections. The results of this analysis are summarised in Table 4.3.

Table 4.3 reveals that the Edwin Swales VC Drive – South Coast Road intersection has the highest estimated rate of dangerous goods accidents and releases, followed by the Bayhead Road – South Coast Road intersection. The Tara Road – Duranta Road, M4 Southern Freeway – Duranta Road and The Avenue East – Refinery Drive intersections have a comparatively lower estimated *Dangerous Goods Accident Rate* and *Dangerous Goods Releasing Accident Rate*. Unfortunately, there are no reliable South African dangerous goods incident databases available to validate these results.

Both the Edwin Swales VC Drive – South Coast Road and the Bayhead Road – South Coast Road intersections have a similar *Proportion of Heavy vehicles transporting Dangerous goods*. However, the Edwin Swales VC Drive – South Coast Road intersection has a higher *Heavy-vehicle Accident Rate* than the Bayhead Road – South Coast Road intersection. There appears to be a proportionate (linear) increase in the estimated *Dangerous Goods Accident Rate* at the Edwin Swales VC Drive – South Coast Road intersection.

The Avenue East – Refinery Drive and the M4 Southern Freeway – Duranta Road intersections have a similar Heavy-*vehicle Accident Rate*. However, the M4 Southern Freeway – Duranta Road intersection has a higher *Proportion of Heavy vehicles transporting Dangerous goods* than The Avenue East – Refinery Drive intersection. There appears to be a proportionate (linear) increase in the estimated *Dangerous Goods Accident Rate* at the M4 Southern Freeway – Duranta Road intersection.

Table 4.3: Dangerous goods accident and release rates at the surveyed intersections, deterministic approach

	Intersection				
Estimated Parameters [units]	**Tara Road – Duranta Road**	**M4 Southern Freeway – Duranta Road**	**The Avenue East – Refinery Drive**	**Bayhead Road – South Coast Road**	**Edwin Swales VC Drive – South Coast Road**
Heavy-vehicle accidents in 3 years	5	12	11	128	297
Heavy-vehicle Accident Rate [Heavy vehicles involved in accidents/year] (4.3)	1.67	4	3.67	43	99
Twelve-hour Weekday traffic volume [Heavy vehicles]	1358	1172	1334	6637	8985
Annual traffic volume [Entering Heavy vehicles/year]	5.20E+05	4.49E+05	5.11E+05	2.54E+06	3.44E+06
Probability of a Heavy-vehicle accident (4.4)	3.20E-06	8.91E-06	7.18E-06	1.68E-05	2.88E-05
# of Heavy vehicles carrying Dangerous goods recorded during 6 hour survey	167	141	57	241	328
# of Heavy vehicles noted during same 6 hour period of eThekwini traffic count	650	671	750	3650	4905
Percentage of Heavy vehicles transporting Dangerous goods (4.5)	25.7%	21.0%	7.60%	6.60%	6.69%
Dangerous Goods accidents/Entering Heavy vehicle (4.6)	8.24E-07	1.87E-06	5.45E-07	1.11E-06	1.92E-06
Entering Heavy vehicles/Dangerous Goods accident (4.7)	1.21E+06	5.34E+05	1.83E+06	9.02E+05	5.20E+05
Years/Dangerous Goods accident (4.8)	**2.33**	**1.19**	**3.59**	**0.355**	**0.151**
Dangerous Goods accidents/year (4.9)	**0.43**	**0.84**	**0.28**	**2.82**	**6.62**
Probability of release given that a Dangerous Goods accident has occurred	0.140	0.140	0.140	0.140	0.140
Releasing Dangerous Goods Accidents/Entering Heavy vehicle (4.10)	1.16E-07	2.63E-07	7.66E-08	1.56E-07	2.70E-07
Entering Heavy vehicles/Releasing Dangerous Goods Accident (4.11)	8.64E+06	3.80E+06	1.31E+07	6.43E+06	3.70E+06
Years/Releasing Dangerous Goods Accident (4.12)	**16.6**	**8.48**	**25.6**	**2.53**	**1.08**
Releasing Dangerous Goods Accidents/year (4.13)	**0.060**	**0.118**	**0.039**	**0.396**	**0.930**

4.1.9 Analysis of deterministic approach

When Equations (4.3) to (4.13) are combined and simplified, the deterministic model for estimating dangerous goods accident and release rates is reduced to two simple relationships:

$$\begin{aligned}&\textit{Dangerous Goods Accident Rate}\\&= \textit{Heavy-vehicle Accident Rate} \times\\&\quad \textit{Proportion of Heavy vehicles transporting Dangerous Goods}\end{aligned} \qquad (4.14)$$

$$\begin{aligned}&\textit{Dangerous Goods Releasing Accident Rate}\\&= \textit{Dangerous Goods Accident Rate} \times\\&\quad \textit{Probability of release} \mid \textit{Dangerous Goods accident}\end{aligned} \qquad (4.15)$$

Checking, using data from the Edwin Swales VC Drive – South Coast Road intersection:

$$\begin{aligned}&\textit{Dangerous Goods Accident Rate}\\&= 99 \times 0.0669 = 6.62 \textit{ Dangerous Goods accidents/year}\\&\textit{Dangerous Goods Releasing Accident Rate}\\&= 6.62 \times 0.140 = 0.93 \textit{ Releasing Dangerous Goods accidents/year}\end{aligned}$$

These results correspond with the values estimated in Section 4.1.5 and Section 4.1.7, respectively. Hence, the linear relationship postulated in Section 4.1.8, between the *Heavy-vehicle Accident Rate*, the *Proportion of Heavy vehicles transporting Dangerous goods* and the *Dangerous Goods Accident Rate* is confirmed.

Henceforth, the *Dangerous Goods Releasing Accident Rate* will be expressed in terms of the recurrence interval, i.e. in units of *Years/Releasing Dangerous Goods accident* instead of *Releasing Dangerous Goods accidents/year.* This decision was taken as readers find it easier to grasp the concept of *2.5 Years/Releasing Dangerous Goods accident*, in comparison to the equivalent of *0.4 Releasing Dangerous Goods accidents/year.*

The approach taken in Sections 4.1.1 to 4.1.7 has clarified the understanding of the system being modelled. Judging purely by the parameters in Equations (4.14) and

(4.15), it would appear that *Exposure* (measured in units of Entering Heavy vehicles/year) has no effect on the *Dangerous Goods Accident Rate* and the *Dangerous Goods Releasing Accident Rate*. The specific manner in which the model has been formulated resulted in the Exposure term being "cancelled out". However, if there are no heavy vehicles entering the intersection, there will be no heavy-vehicle accidents. Thus, *Exposure* and *Accident Rate* are clearly not independent of each other.

4.1.10 Application of deterministic approach to specific chemicals

The deterministic approach discussed in Sections 4.1.1 to 4.1.9 may be adapted to estimate the dangerous goods accident and release rates for specific chemicals.

- **Petroleum**

Petroleum (UN No. 1203) was the primary dangerous substance identified during the surveys. During the six-hour survey at the Edwin Swales VC Drive – South Coast Road intersection, 129 Petroleum tankers were recorded (Appendix B: Table: B.2). Substituting this parameter into Equation (4.5) yields:

$$\begin{aligned}&\textit{Proportion of Heavy vehicles transporting Petroleum}\\&= \frac{129}{4905} = 0.0263 \textit{ Petroleum tankers/Entering Heavy vehicle}\end{aligned}$$

Substituting the proportion of heavy vehicles transporting Petroleum into Equation (4.14), yields:

$$\begin{aligned}&\textit{Petroleum tanker Accident Rate}\\&= 99 \times 0.0263 = 2.60 \textit{ Petroleum tankers involved in accidents/year}\end{aligned}$$

Substituting the *Petroleum tanker Accident Rate* into Equation (4.15) yields:

$$\begin{aligned}&\textit{Petroleum tanker Releasing Accident Rate}\\&= 2.60 \times 0.140\\&= 0.366 \textit{ Releasing Petroleum tanker accidents/year}\\&\equiv 2.74 \textit{ Years/Releasing Petroleum tanker accident, at the Edwin Swales VC}\\&\textit{Drive - South Coast Road intersection}\end{aligned}$$

- **Tetra Ethyl Lead**

Tetra Ethyl Lead (UN No. 1649) is allocated to Danger group I (substances that present a very severe risk). During the six-hour survey at the Edwin Swales VC Drive – South Coast Road intersection, two Tetra Ethyl Lead tankers were recorded (Appendix B: Table: B.2). Substituting this parameter into Equation (4.5) yields:

$$\textit{Proportion of Heavy vehicles transporting Tetra Ethyl Lead}$$
$$= \frac{2}{4905} = 0.0004 \textit{ Tetra Ethyl Lead tankers/Entering Heavy vehicle}$$

Substituting the proportion of heavy vehicles transporting Tetra Ethyl Lead into Equation (4.14), yields:

$$\textit{Tetra Ethyl Lead tanker Accident Rate}$$
$$= 99 \times 0.0004$$
$$= 0.04 \textit{ Tetra Ethyl Lead tankers involved in accidents/year}$$
$$\equiv 25 \textit{ Years/Tetra Ethyl Lead tanker accident}$$

Substituting the *Tetra Ethyl Lead tanker Accident Rate* into Equation (4.15) yields:

$$\textit{Tetra Ethyl Lead tanker Releasing Accident Rate}$$
$$= 0.04 \times 0.140$$
$$= 0.006 \textit{ Releasing Tetra Ethyl Lead tanker accidents/year}$$
$$\equiv 176 \textit{ Years/Releasing Tetra Ethyl Lead tanker accident, at the Edwin Swales VC Drive - South Coast Road intersection}$$

Tetra Ethyl Lead and the other Danger group I substances being transported through the selected intersections, present a very severe risk. However, as the proportion of heavy vehicles transporting these substances is low (compared to Petroleum for example), the estimated frequency of accidents and releases involving Danger group I substances is much lower.

4.2 Monte Carlo Simulation of Dangerous Goods Accidents

4.2.1 Background and approach

As described in Chapter 2, many researchers have developed and applied methods to evaluate the risks associated with dangerous goods transport. In most cases, these methods required extensive and reliable data sources. Probabilities and parameter values were usually assumed to be known, deterministic values. However, transportation risk assessments must often be performed even when there are substantial data uncertainties.

An important caveat for researchers is the effect of under-reporting of accidents. The number of accidents *reported* to the authorities, and hence, the estimated accident rate, may be far less than the number of accidents that actually occur at a location. Hauer & Hakkert [1988] studied the effects of under-reporting and estimated that fatal accident records were accurate to within 5 per-cent, serious injury accident records to within 20 per-cent, and minor injury records to within 50 per-cent. The reporting of accidents varies with the driver, the location and time of the accident, and the accident severity [Hauer & Hakkert, 1988].

The deterministic model for estimating dangerous goods accident and release rates at intersections, described in Section 4.1, has three input parameters:

- *Heavy-vehicle accident rate*
- *Proportion of heavy vehicles transporting dangerous goods*
- *Probability of release given that a dangerous goods accident has occurred*

The values of these input parameters of the deterministic model are not known with certainty. Hence, the need for an analysis method that explicitly incorporates this uncertainty became apparent.

When the input parameters of the deterministic model are held constant, the same results are obtained no matter how many times the model is recalculated. Monte Carlo simulation was employed to iteratively evaluate the deterministic model. Specific probability distributions were chosen for each of the input parameters. The probability distribution chosen for each input parameter either closely matched the existing data, or best represented the current state of knowledge. The inputs for each recalculation of the *now stochastic* model were then randomly generated from the chosen probability distributions, to simulate the process of sampling from an actual population. A stochastic model is a model that incorporates probability or randomness [Kalos & Whitlock, 1986]. The process used to select the probability distributions for each of the input parameters is outlined in this section. The Edwin Swales VC Drive – South Coast Road intersection is again used as an example.

4.2.2 Heavy-vehicle accident rate

The most recent three-year record of heavy-vehicle accidents at the Edwin Swales VC Drive – South Coast Road intersection was obtained from the eThekwini Municipality Transport Authority. The annual records of accidents involving single-unit heavy vehicles, articulated heavy vehicles and multiple-articulated heavy vehicles, for the period 1 January 2000 to 31 December 2002, are presented in Table 4.4. Vehicle-pedestrian accidents were not included in this investigation as, intuitively, and from the evidence of Table 4.2, they have a very low probability of resulting in a dangerous goods release.

Table 4.4: Breakdown of heavy-vehicle accidents at the Edwin Swales VC Drive – South Coast Road intersection, 2000-2002

	# of Heavy-vehicle accidents		
Heavy-vehicle type	**2000**	**2001**	**2002**
Multiple-articulated heavy vehicle	27	16	11
Articulated heavy vehicle	43	65	67
Single-unit heavy goods vehicle	18	23	27
Σ	88	104	105

The historical record presented in Table 4.4 illustrates variability in the count of accidents within each heavy-vehicle type over the three-year period. Unfortunately, due to the random nature of accidents, inferring a potential for accidents at a given intersection solely from the historical accident data, may yield spurious results [Vogt, 1999]. Most locations do not experience many accidents in any given year (some of the surveyed intersections in this investigation fall into this category). Observations may be too infrequent and too variable to yield meaningful and reliable long-term results. In addition, simple linear regression is generally not regarded as an appropriate statistical approach for modelling accident relationships because accidents are discrete, random, non-negative events that often do not follow a Normal distribution [Vogt, 1999]. Accidents are described as discrete, random events because the length of time until the next accident occurs does not depend on how long it has been since the last accident occurred [Vogt, 1999].

In recent years, a consensus has formed in favour of modelling accidents as rare, independent events [Vogt, 1999]. Such events may be characterised by their mean λ per unit time and are simply represented by a random variable with a Poisson distribution, i.e., the probability that *y* accidents will be observed per unit time is:

$$P(Y = y) = \frac{e^{\lambda}\lambda^{y}}{y!} \tag{4.16}$$

where: y = 0, 1, 2 ... accidents per unit time

The Poisson distribution is often used to simulate the number of times that an event will happen when there is no clear upper bound on how many times it might happen. Poisson models provide an easy linkage to probability, as opposed to other commonly used accident models such as linear regression [Vogt & Bared, 1998].

A *Poisson process* does not mean the same thing a *Poisson distribution*. The association of Poisson distributed random variables with intervals of time characterises a *1-dimensional Poisson process.* Let the *intensity* of this particular 1-dimensional Poisson process, be λ per unit time. In any time period of length T, the number of accidents is a Poisson random variable with mean λT. The numbers of accidents in separate periods of time are independent of each other. In such a Poisson process, the times between successive accidents are independent continuous Exponential random variables with a mean 1/λ [Vogt & Bared, 1998].

One caveat of the using the Poisson process to model the *Heavy-vehicle Accident Rate* is that it restricts the mean and variance of the accident frequency data to be equal. This is often not the case with historical accident frequency data. Such data are often characterised by overdispersion (the variance of the accident frequency exceeds the mean). The use of a Negative Binomial distribution to model the *Heavy-vehicle Accident Rate*, relaxes this mean/variance equality restriction and accordingly accounts for overdispersed data. The choice between using the Poisson or the Negative Binomial distribution is based on the overdispersion observed in the historical accident data [Vogt, 1999]. Negative Binomial models have been successfully applied to estimate the frequency of traffic accidents on roadway segments and at intersections [Yinhai et al. 2003].

Many previous studies have used Poisson and Negative Binomial accident models. Hakkert & Mahalel [1978] used a Poisson model to study accidents at intersections. Pickering et al. [1986], in a study of accidents at three-legged intersections, used a Poisson model along with a generalised linear modelling technique. Maycock & Hall [1984] studying traffic circles and Hauer, Ng & Lovell [1988] studying urban intersections, employed the Negative Binomial technique. Other studies that have used Negative Binomial models include: Bauer & Harwood [1996] for studying accidents at intersections and Vogt & Bared [1998] for studying accidents at rural intersections and on rural segments.

Another characteristic of accident frequency data is a large number of zeros resulting from not having an accident occur at a specific location, in a given time period. Some researchers have applied two-state models – one state that has near zero accident probability and another state follows a Poisson or Negative Binomial distribution [Yinhai et al. 2003]. Bauer & Harwood [1996] in addition to employing Poisson and Negative Binomial modelling also presented a Lognormal model, where the natural logarithm of the number of accidents is regarded as a Normal variable with mean μ and variance σ^2. They found this model useful where intersections had very few accidents in the time period under consideration (some of the surveyed intersections in this investigation fall into this category).

The parameters of the *Heavy-vehicle Accident Rate* were calculated from Table 4.4:

Mean λ = *99 Heavy vehicle accidents/year*

Variance = *91*

The variance of this accident frequency data does not exceed the mean, i.e. the data is not overdispersed. Hence, there was no need to use a Negative Binomial distribution to model the accident rate. Therefore, the decision was taken to model the *Heavy-vehicle Accident Rate* at the Edwin Swales VC Drive – South Coast Road intersection as a Poisson random variable with *mean* λ = *99* Heavy-vehicle accidents/year

4.2.3 Proportion of heavy vehicles transporting dangerous goods

A breakdown of the proportion of heavy vehicles transporting dangerous goods, during each of the six hours of the survey at the Edwin Swales VC Drive – South Coast Road intersection, is presented in Table 4.5.

Table 4.5: Hourly breakdown of the proportion of heavy vehicles transporting dangerous goods, Edwin Swales VC Drive – South Coast Road intersection

Hour ending	# of Heavy vehicles transporting Dangerous goods	Estimated # of entering heavy vehicles	Proportion of Heavy vehicles transporting Dangerous goods
08:40	42	721	0.0583 (5.83%)
09:40	64	829	0.0772 (7.72%)
10:40	59	814	0.0725 (7.25%)
11:40	68	829	0.0821 (8.21%)
12:40	62	873	0.0710 (7.10%)
13:40	33	839	0.0393 (3.93%)
Σ	328	4905	0.0669 (6.69%)

The parameters of the *Proportion of heavy vehicles transporting dangerous goods* were calculated from Table 4.5:

Mean μ = 0.0667

Standard deviation σ = 0.0156

The proportion of heavy vehicles transporting dangerous goods in Table 4.5, did not show a great deal of variability over the course of the six-hour survey. The Lilliefors test for goodness-of-fit to a Normal distribution was performed on the sample of six values from the rightmost column of Table 4.5. More information on the Lilliefors test and the technique for performing this test in Microsoft Excel™ is presented in Sections 4.3.2 and 4.3.3. The null hypothesis, that the proportion of heavy vehicles transporting dangerous goods at the Edwin Swales VC Drive – South Coast Road intersection, followed a Normal distribution, could not be rejected at the α = 0.05 level of significance. In addition, the calculated *p-value* (interpolated from the relevant table in [Daniel, 1990]) was approximately 0.16, so the null hypothesis was not rejected. The *p-value* is the probability of observing the given sample result under the assumption that the null hypothesis is true. If the p-value is less than the α level of significance, then the null hypothesis is rejected. If the p-value is greater than α, then there is insufficient evidence to reject the null hypothesis [Conover, 1980].

Hence, the decision was taken to model the *Proportion of heavy vehicles transporting dangerous goods* at the Edwin Swales VC Drive – South Coast Road intersection, as a Normal random variable with *mean* $\mu = 0.0667$ and *standard deviation* $\sigma = 0.0156$.

The usual justification for using the Normal distribution for modelling is the Central Limit Theorem, which states (roughly) that if a large number of independent samples is taken from virtually any probability distribution, the mean values of these independent samples will follow a probability distribution that is approximately Normal [Daniel, 1990].

4.2.4 Probability of release

No South African statistics were available to estimate the probability of release given an accident involving a dangerous goods vehicle. The dangerous goods release probabilities presented in Table 4.1 and Table 4.2, which were based on information reported to the U.S. FHWA, were studied.

In Table 4.1, *at-grade intersection accidents* were shown to have a 3.5 per-cent probability of resulting in a dangerous goods release. On average, 14 per-cent of *all* accidents involving dangerous goods carrying heavy vehicles resulted in a release. The three-year record of accidents involving heavy vehicles at the Edwin Swales VC Drive – South Coast Road intersection included a *Single-vehicle Overturned* accident in 2001. Table 4.2 reported that such accidents in the U.S. had a 37.5 per-cent probability of resulting in a dangerous goods release. In addition, road tanker vehicles involved in serious accidents usually do not remain upright [Eurochlor, 1998].

Hence, the decision was taken to model the probability of release given that a dangerous goods accident has occurred, at the Edwin Swales VC Drive – South Coast Road intersection, as a Uniform random variable between the *lower bound* $A = 0.035$ and the *upper bound* $B = 0.375$.

A Uniform distribution was selected because there was complete uncertainty as to which values within the range were more likely under South African conditions. As discussed in Section 2.7.3, Pet-Armacost et al. [1999] used Monte Carlo simulation to investigate the risks associated with transporting the chemical Hydrazine in tanks, with and without pressure relief devices fitted. No data was available on the following factors: the impact of relief devices on release probabilities; and the impact of

Hydrazine on the likelihood of fires and explosions. Faced with similar data uncertainties, Pet-Armacost et al. [1999] also made use of Uniform distributions to model these factors.

4.2.5 Generation of random variables

Computer-generated random numbers are not true random numbers, as computers are deterministic. However, given a number to start with, called a *random number seed*, a series of mathematical operations are performed on this seed in order to generate unrelated "pseudo" random numbers. If a random number seed is used more than once, identical random numbers will be generated each time. Thus, for multiple trials, different random number seeds must be used. Many random number generators draw a random number seed from somewhere within the system, e.g. the time on the computer clock, therefore the seed is unlikely to be the same for two different experiments [Hellekalek, 2004].

The output of random number generators is usually tested with rigorous statistical tests to ensure that the numbers are actually random in relation to one another. There is much concern that the statistical algorithms used in Microsoft Excel™ yield erroneous results and that the procedures for random number generation do not reach an acceptable standard [Knüsel, 1998; McCullough & Wilson, 1999]. Hence, *PopTools*, a freeware enhancement or *add-in* to Microsoft Excel™ was utilised in this investigation. PopTools includes routines for generation of random variables from various distributions, e.g. Normal, Poisson, Binomial, Lognormal, Gamma, Exponential, etc. All PopTools functions and procedures that depend on random variables use the *Mersenne Twister* pseudo-random number generator (PRNG) developed by Matsumoto & Nishimura [1998]. The Mersenne Twister PRNG has undergone thorough testing and been proven to have excellent statistical properties [Hellekalek, 2004; Matsumoto & Nishimura, 1998]. Ultimately, a computer cannot express an infinite state. Pseudo-random numbers will eventually return to the initial value in a certain cycle, which is called the *period* of the random numbers. One of the characteristics of Mersenne Twister PRNG is its very long period of $2^{19937}-1$ [Matsumoto & Nishimura, 1998]. Many researchers in the field of random number generation consider the Mersenne Twister to be the best PRNG available for stochastic simulation [Hellekalek, 2004].

4.2.6 Overview of stochastic model

Monte Carlo simulation was employed to iteratively evaluate the deterministic model presented in Section 4.1.9. The input parameters for each recalculation of the *now stochastic* model were randomly generated from the selected probability distributions presented in Table 4.6.

Table 4.6: Input parameters for Monte Carlo simulation of dangerous goods accidents and releases at the Edwin Swales VC Drive – South Coast Road intersection

Input parameter	Selected distribution	Distribution parameters
Heavy-vehicle accident rate	Poisson random variable	Mean λ = 99
Proportion of Heavy vehicles transporting dangerous goods	Normal random variable	Mean μ = 0.0667 Standard deviation σ = 0.0156
Probability of release | Dangerous goods accident	Uniform random variable	Lower bound A = 0.035 Upper bound B = 0.375

The popularity of Monte Carlo methods has led to a number of commercial simulation programs, which work directly with Microsoft Excel™ spreadsheets as add-ins. Crystal Ball™ and @Risk™ are the two most popular and are very costly (approximately US$700). Due to their ease of use and the user's possible lack of familiarity with the underlying assumptions and restrictions, it is easy to misuse such commercial simulation packages by "stretching" them beyond the limits of credibility. Slick graphics, animation, tables, etc. tempt the user to assign unwarranted credibility to the output [Pet-Armacost et al. 1999].

Fortunately, Monte Carlo simulation may be easily performed in Microsoft Excel™ without purchasing commercial simulation packages. The *Column-input Data: Table* procedure in a spreadsheet may be used to tabulate the outputs from repeated independent recalculations of a stochastic model. However, the resultant Microsoft Excel™ data tables are "alive", i.e. they are recalculated every time the spreadsheet is recalculated (when the [F9] OR [Enter] keys are pressed) because the input parameters are random variables. When performing statistical analysis, the following steps should be taken to prevent the simulated data from changing after the simulation is completed:

- Select the data range and copy it to the clipboard using the *Edit: Copy* command
- Use the *Edit: Paste Special: Values* command on the selected data range.

The result is that the formulas in the data range are replaced by the values that were displayed, and these numerical values will not change.

Myerson [2001] developed *Simtools.xla*, a free downloadable Microsoft Excel™ add-in comparable to @Risk™ and Crystal Ball™, for performing Monte Carlo simulations. Simtools.xla adds a *Simulation Table* procedure to the Tools menu in Microsoft Excel™. This procedure tabulates outputs from repeated independent recalculations of a stochastic spreadsheet model. Simulation Table is similar to a column-input data table, but Simulation Table stores the output data as values that are not recalculated whenever the spreadsheet changes. In fact, the Simulation Table procedure merely tells Microsoft Excel™ to carry out a Data: Table command followed by a Copy and Paste-Special-Values command. Simulation Table also adds a column containing a percentile index to the output data; indicating (in each row of the output table) what fraction of the simulation data is above this row. This is useful for making empirical cumulative distribution charts after sorting the output data.

4.2.7 Monte Carlo simulation results

The results of one thousand independent recalculations of the stochastic model for estimating dangerous goods accident and release rates at the Edwin Swales VC Drive – South Coast Road intersection, are summarised in Figure 4.1 and Figure 4.2.

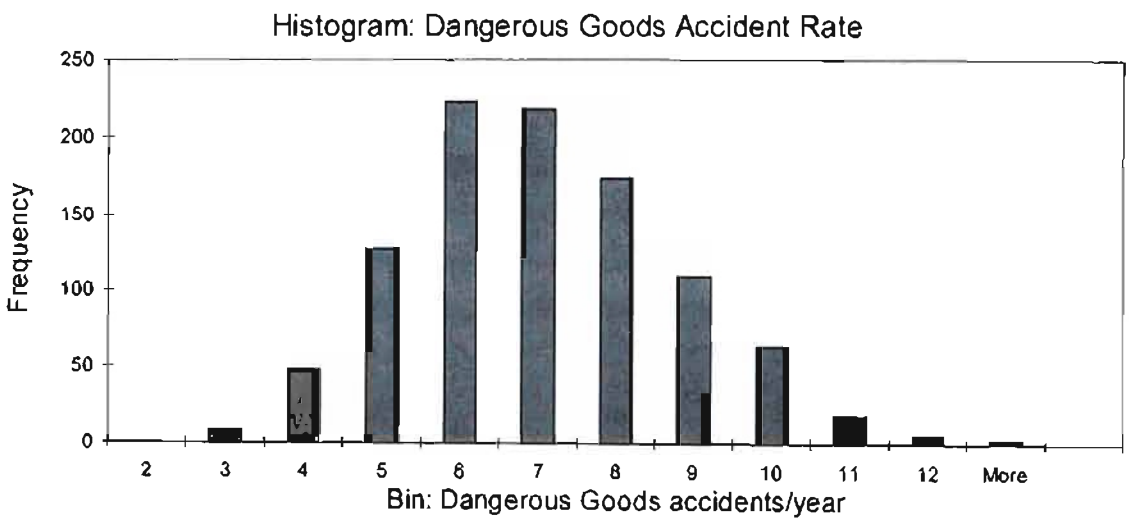


Figure 4.1: Distribution of the *Dangerous Goods Accident Rate* at the Edwin Swales VC Drive – South Coast Road intersection

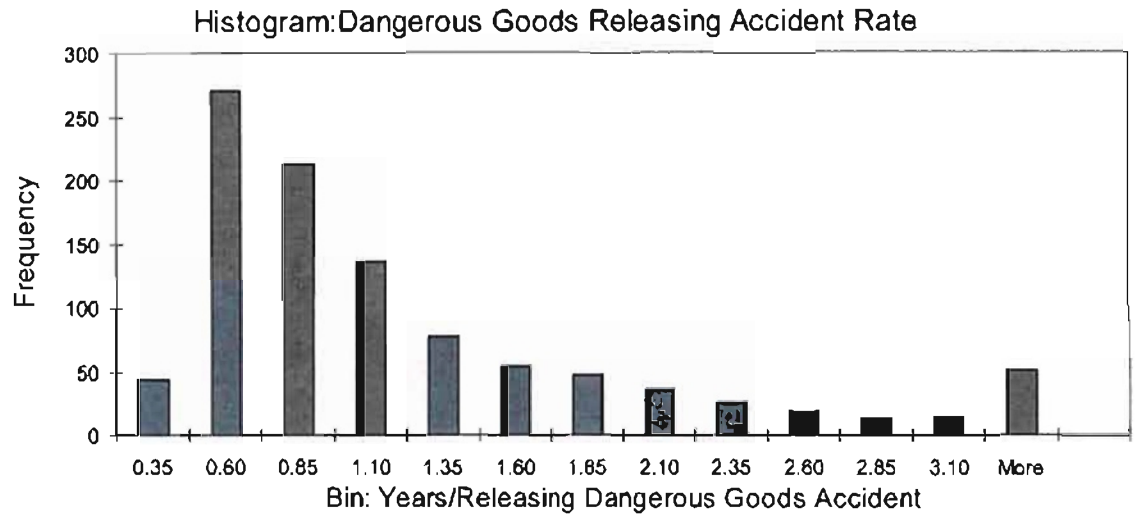


Figure 4.2: Distribution of the *Dangerous Goods Releasing Accident Rate* at the Edwin Swales VC Drive – South Coast Road intersection

Graphs of the empirical cumulative distribution function of the output parameters are another means of conveying the results of a Monte Carlo simulation. The empirical cumulative distribution function, *S(x)* may be calculated from the sample data using the following [Daniel, 1990]:

$$S(x) = \frac{\text{the number of sample observations } \leq x}{n} \tag{4.17}$$

where:

S(x) = the proportion of sample observations less than or equal to *x*

n = the total number of sample observations

S(x) is a step function that increases by a value of 1/*n* at each ordered data point [Daniel, 1990].

The empirical cumulative distribution functions of the *Dangerous Goods Accident Rate* and the *Dangerous Goods Releasing Accident Rate* are presented in Figure 4.3 and Figure 4.4, respectively.

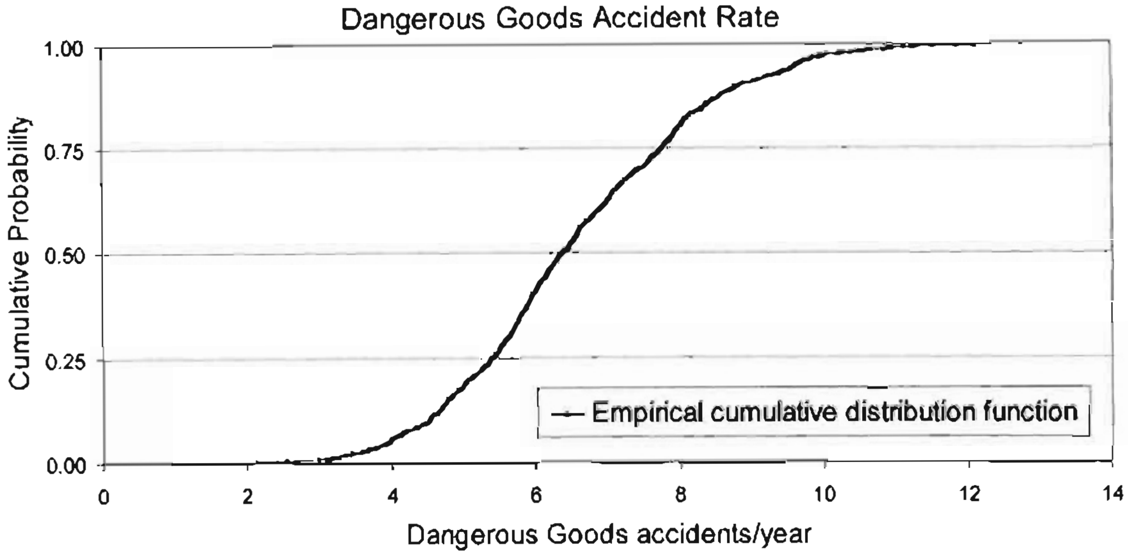


Figure 4.3: The empirical cumulative distribution function of the *Dangerous Goods Accident Rate*, Edwin Swales VC Drive – South Coast Road intersection

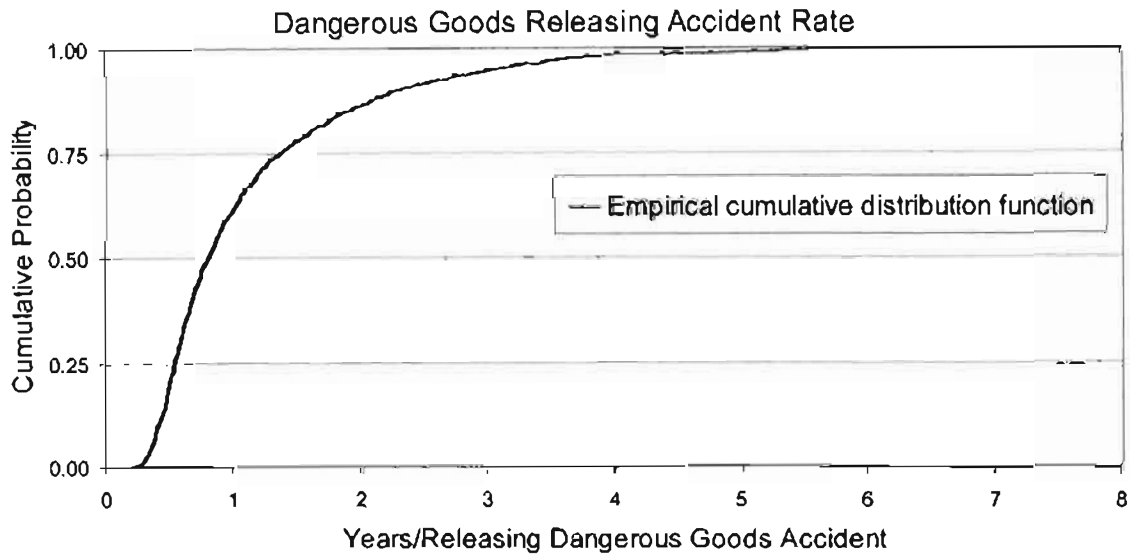


Figure 4.4: The empirical cumulative distribution function of the *Dangerous Goods Releasing Accident Rate*, Edwin Swales VC Drive – South Coast Road intersection

Accidents occur at random points in time, and the length of time between any particular accident and the next accident is a random variable. Nevertheless, Figure 4.4 illustrates that in 75 per-cent of cases, the length of time between one *releasing dangerous goods accident* and the next will be less than 1.5 years, at the Edwin Swales VC Drive – South Coast Road intersection.

The output of the Monte Carlo simulation was analysed statistically and the results of this analysis are presented in Table 4.7.

Table 4.7: Statistical analysis of Monte Carlo simulation, Edwin Swales VC Drive – South Coast Road intersection

Descriptive statistics	**Dangerous Goods Accident Rate** [Dangerous Goods accidents/year]	**Dangerous Goods Releasing Accident Rate** [Years/Releasing Dangerous Goods Accident]
Mean	6.57	1.15
Median	6.38	0.81
Standard Deviation	1.73	0.98
Variance	2.98	0.95
Minimum	1.82	0.22
Maximum	12.76	8.26
Count	1000	1000

Table 4.7 reveals that in any given year at the Edwin Swales VC Drive – South Coast Road intersection, there may be:

- up to twelve accidents involving dangerous goods carrying heavy vehicles
- up to four accidents involving heavy vehicles where dangerous goods are released.

However, the results presented in Table 4.7 are not *true* maxima and minima. Performing a Monte Carlo simulation with one million recalculations of the stochastic model for example, may yield new maxima and minima, as more model inputs are sampled from the extremes of the input parameter population distributions.

4.2.8 Comparison of deterministic model and Monte Carlo simulation

A summary of the estimated dangerous goods accident and release rates at the Edwin Swales VC Drive – South Coast Road intersection, estimated using both the deterministic model and Monte Carlo simulation, is presented in Table 4.8.

Table 4.8: Comparison of the results of the deterministic approach and Monte Carlo simulation, Edwin Swales VC Drive – South Coast Road intersection

Estimated Parameter	Deterministic Model	Monte Carlo Simulation
Heavy-vehicle Accident Rate [Heavy vehicles involved in accidents/year]	99	Poisson random variable with Mean λ = 99
Proportion of Heavy vehicles transporting dangerous goods	0.0669	Normal random variable with Mean μ = 0.0667 and Standard deviation σ = 0.0156
Dangerous Goods Accident Rate [Dangerous Goods accidents/year]	6.62	Mean value = 6.57
Probability of release | Dangerous goods accident	0.140	Uniform random variable between Lower bound A = 0.035 and Upper bound B = 0.375
Dangerous Goods Releasing Accident Rate [Years/Releasing Dangerous Goods Accident]	1.08	Mean value = 1.15

The mean values of the *Dangerous Goods Accident Rate* and the *Dangerous Goods Releasing Accident Rate* estimated using Monte Carlo simulation, are quite similar to those results estimated using the deterministic model in Section 4.1.5 and Section 4.1.7. However, Figure 4.2 clearly illustrates that the highest probability densities of the *Dangerous Goods Releasing Accident Rate* occur in the range 0.35–0.85 Years/Releasing dangerous goods accident, and not at the mean value of 1.15 Years/Releasing dangerous goods accident.

Essentially, the deterministic model produced two numbers: expected values of the *Dangerous Goods Accident Rate* and the *Dangerous Goods Releasing Accident Rate*. Further advantages of the application of Monte Carlo simulation have been revealed in this section. Utilising the same raw data as the deterministic approach, coupled with justifiable assumptions based on the available data, Monte Carlo simulation has actually provided the researcher with far more information. Moreover, available information that would otherwise be ignored or aggregated, has been incorporated into this investigation. Thus, in comparison to the deterministic models typically used in transportation risk assessments, Monte Carlo simulation enables a more detailed understanding of the nature and distribution of dangerous goods accidents and releases.

4.3 Application of Central Limit Theorem to Monte Carlo simulation results

4.3.1 Lognormal distributions

When the conditions of the Central Limit Theorem are fulfilled, the mathematical process of multiplying a series of random variables will produce a new random variable (the product), which tends *in the limit* to be Lognormal in character, regardless of the distributions from which the input variables arise [Benjamin & Cornell, 1970].

The Lognormal and Normal distributions are closely related. By definition, a data vector $\underline{Y}$ is said to have a Lognormal distribution, if its natural logarithm $ln(\underline{Y})$ has a Normal distribution. The Lognormal distribution is skewed to the right. For a given *mean* μ, the skewness increases as the *standard deviation* σ increases [Daniel, 1990]. Figure 4.5 presents the probability density functions for fictitious Lognormal data.

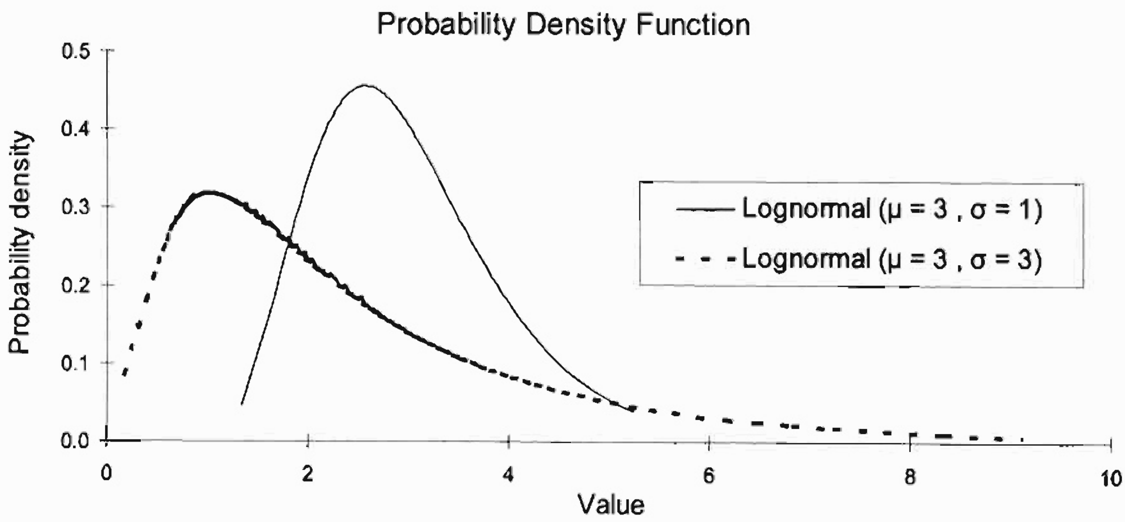


Figure 4.5: Probability density functions for fictitious Lognormal data

By visual inspection, the histograms of the *Dangerous Goods Accident Rate* and the *Dangerous Goods Releasing Accident Rate* plotted in Figure 4.1 and Figure 4.2, respectively, appear Lognormal in character.

The nature of the population distributions of the *Dangerous Goods Accident Rate* and the *Dangerous Goods Releasing Accident Rate*, are of great interest to this investigation. Ideally, a researcher would wish to make a statement like: "the *Dangerous Goods Accident Rate* at the Edwin Swales VC Drive – South Coast Road intersection follows a Lognormal distribution with *mean μ* = *X* and *standard deviation σ* = *Y*" (where *X* and *Y* are floating-point numbers). Hence, the proposal that the *Dangerous Goods Accident Rate* and the *Dangerous Goods Releasing Accident Rate* follow a Lognormal distribution, was investigated.

As discussed in Section 4.2.7, the Monte Carlo simulation consisted of one thousand independent recalculations of the stochastic model for estimating dangerous goods accident and release rates. Hence, the *Dangerous Goods Accident Rate* consists of a sample size of one thousand. The natural logarithm of each of these one thousand values of the *Dangerous Goods Accident Rate* was calculated. This step was repeated for each value of the *Dangerous Goods Releasing Accident Rate.* These natural logarithms were analysed statistically and the results of this analysis are presented in Table 4.9.

Table 4.9: Further statistical analysis of the Monte Carlo simulation, Edwin Swales VC Drive – South Coast Road intersection

	Dangerous Goods Accident Rate ***ln*[Dangerous Goods accidents/year]**	Dangerous Goods Releasing Accident Rate ***ln*[Years/Releasing Dangerous Goods Accident]**
Mean	1.85	-0.11
Standard Deviation	0.27	0.66
Count	1000	1000

If the *Dangerous Goods Accident Rate* is Lognormally distributed, by definition, the natural logarithms of *Dangerous Goods accidents/year* will be Normally distributed. Similarly, if the *Dangerous Goods Releasing Accident Rate* is Lognormally distributed, the natural logarithms of *Years/Releasing Dangerous Goods Accident* will be Normally distributed.

A comparison was made of: the empirical cumulative distribution function of *ln[Dangerous Goods accidents/year]*; and the cumulative distribution function (CDF) of a hypothesised Normal distribution with parameters *mean μ = 1.85* and *standard deviation σ = 0.27* (taken from Table 4.9). The results of this comparison are presented in Figure 4.6.

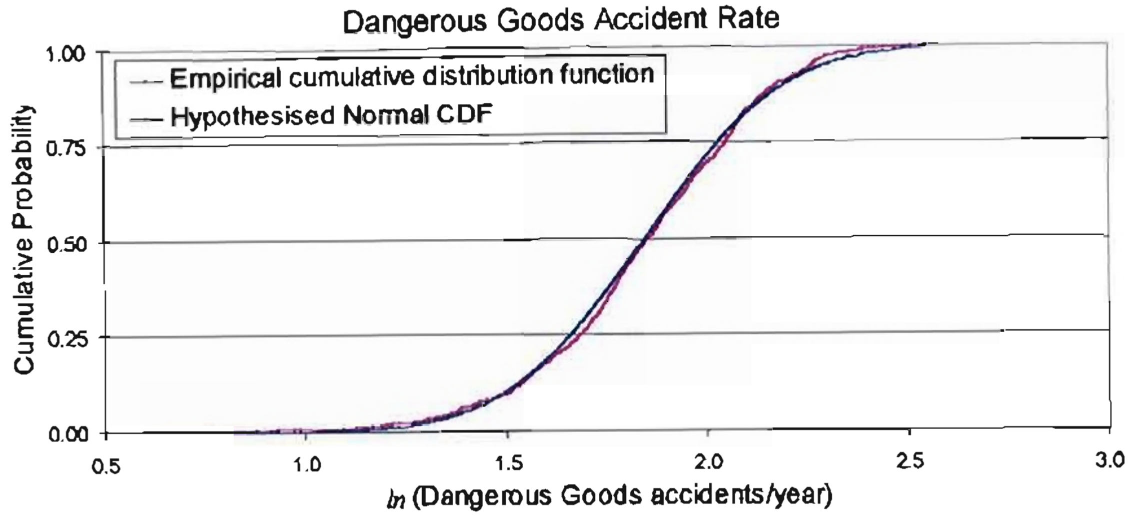


Figure 4.6: Comparison of the empirical cumulative distribution function of *ln[Dangerous Goods accidents/year]* and the cumulative distribution function of the hypothesised Normal distribution, Edwin Swales VC Drive – South Coast Road intersection

The Central Limit Theorem states that the product of a series of random variables tends *in the limit* to be Lognormal in character [Benjamin & Cornell, 1970]. The formula for calculating the *Dangerous Goods Accident Rate*, Equation (4.14) contains just two random variables, yet the two plotted cumulative distribution functions in Figure 4.6 appear very similar.

A comparison was made of: the empirical cumulative distribution function of *ln[Years/Releasing Dangerous Goods Accident]*; and the cumulative distribution function of a hypothesised Normal distribution with parameters *mean* μ = *-0.11* and *standard deviation* σ = *0.66* (taken from Table 4.9).The results of this comparison are presented in Figure 4.7.

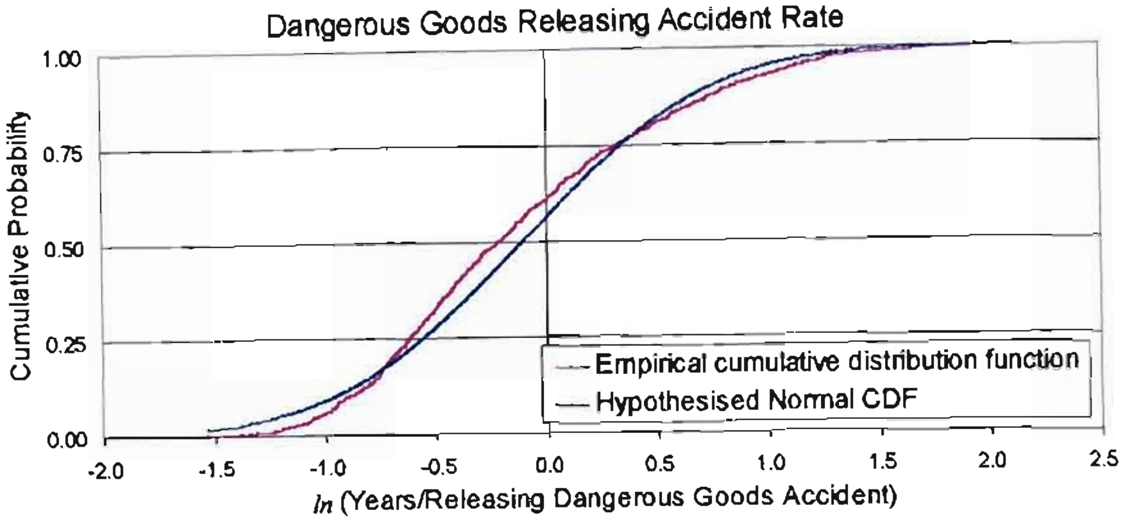


Figure 4.7: Comparison of the empirical cumulative distribution function of *ln[Years/Releasing Dangerous Goods Accident]* and the cumulative distribution function of the hypothesised Normal distribution, Edwin Swales VC Drive – South Coast Road intersection

The formula for calculating the *Dangerous Goods Releasing Accident Rate*, Equation (4.15) contains three random variables, yet the two plotted cumulative distribution functions in Figure 4.7 are not as similar as the two curves plotted in Figure 4.6. Clearly, a quantitative assessment of these qualitative observations is required.

4.3.2 Kolmogorov-Smirnov one-sample goodness-of-fit test

Goodness-of-fit tests are a means of establishing how well the observed sample data "fit" some proposed distribution [Conover, 1980]. The goodness-of-fit test applied in this investigation was used to establish whether the Monte Carlo simulated *Dangerous Goods Accident Rate* and *Dangerous Goods Releasing Accident Rate* at the Edwin Swales VC Drive – South Coast Road intersection, follow a Lognormal distribution.

The Kolmogorov-Smirnov (KS) test was designed for testing the goodness-of-fit for continuous data. One distinction of the KS test is that it makes no assumption about the underlying cumulative distribution function of the data being tested. Technically speaking it is *nonparametric* or distribution-free [Conover, 1980]. Nonparametric statistical procedures have several advantages over parametric procedures. As most nonparametric procedures depend on a minimum of assumptions, the likelihood of them being improperly used is reduced. Nonparametric procedures may be applied when data are measured on a weak measurement scale, e.g. when only rank data or count data are available for analysis [Daniel, 1990].

The Kolmogorov-Smirnov one-sample goodness-of-fit test focuses on two cumulative distribution functions: a hypothesised cumulative distribution and the sample (empirical) cumulative distribution. $F(x)$ is generally used to designate a cumulative distribution function. For a given x, $F(x)$ is the probability that the value of the random variable X is less than or equal to x; that is, $F(x) = P(X \leq x)$ [Conover, 1980].

Let $F_0(x)$ be a hypothesised cumulative distribution function. A random sample is drawn from some unknown distribution, $F(x)$. The aim is to establish if $F(x) \neq F_0(x)$ for all x. If $F(x) = F_0(x)$, close agreement is expected between $F_0(x)$ and the sample (empirical) cumulative distribution function, $S(x)$. The objective of the Kolmogorov-Smirnov one-sample goodness-of-fit test is to establish whether the lack of agreement between $F_0(x)$ and $S(x)$ is sufficient to cast doubt on the hypothesis that $F(x) = F_0(x)$ [Conover, 1980].

The null hypothesis (H_0) and alternative hypothesis (H_1) for the Kolmogorov-Smirnov one-sample goodness-of-fit test are as follows [Conover, 1980]:

H_0: $F(x) = F_0(x)$ for all values of x

H_1: $F(x) \neq F_0(x)$ for at least one value of x

A hypothesis may be defined as a "statement about one or more populations." Two statistical hypotheses exist: the *null hypothesis* (which is designated H_0) and the *alternative hypothesis* (which is designated H_1). The null hypothesis is the hypothesis that is tested. The null hypothesis is usually the statement of no difference. For example, the null hypothesis may state that one population is identical to another with respect to some characteristic. A null hypothesis is presumed to be true until sufficient evidence to reject it has been amassed [Conover, 1980].

The goodness-of-fit test procedure is based on information derived from the data of an appropriate sample. The test procedure results in one of two outcomes:

- A decision to reject the null hypothesis as false
- A decision not to reject the null hypothesis because the sample does not provide sufficient evidence to warrant rejection.

When the null hypothesis is rejected, the alternative hypothesis is accepted as true. This is possible if the null hypothesis and the alternative hypothesis are stated in such a way that they are mutually exclusive and complementary [Conover, 1980].

To test a null hypothesis (H_0), an appropriate test statistic is selected and its distribution specified when H_0 is true. The value of the test statistic is calculated from the observed sample data. Before examining the sample data, a decision rule is formulated. This rule states that H_0 will be rejected if the probability of obtaining a value of the test statistic of a given or more extreme magnitude, when H_0 is true, is equal to or less than some small number α. When the decision rule approach is used, α (commonly referred to as the *level of significance*) is usually chosen to be 0.05, 0.01 or occasionally 0.10 [Daniel, 1990]. For example, at a typical significance level of α = 0.05, the probability of incorrectly rejecting the null hypothesis, when it is actually true, is 5 per-cent.

Alternatively, the decision rule may be stated in terms of critical values. The *critical value* of the test statistic is the value that is so extreme that the probability of getting this value or a more extreme value, when H_0 is true, is equal to α. For example, in a one-sided test, H_0 is rejected if the calculated value of the test statistic is as extreme as or more extreme than the critical value [Conover, 1980].

The test statistic for the Kolmogorov-Smirnov one-sample goodness-of-fit test is calculated as:

$$D = \max_{x} \left| S(x) - F_0(x) \right| \tag{4.18}$$

Which is read "*D* equals the maximum, over all *x*, of the absolute value of the difference $S(x) - F_0(x)$." When the two cumulative distribution functions are represented graphically, *D* is the greatest vertical distance between $S(x)$ and $F_0(x)$. The null hypothesis (H_0) is rejected at the α significance level if the test statistic, *D* exceeds the value shown in the relevant statistical table [Daniel, 1990]. Figure 4.8 is a graph of fictitious data showing the two functions $S(x)$ and $F_0(x)$ and the KS test statistic, *D*.

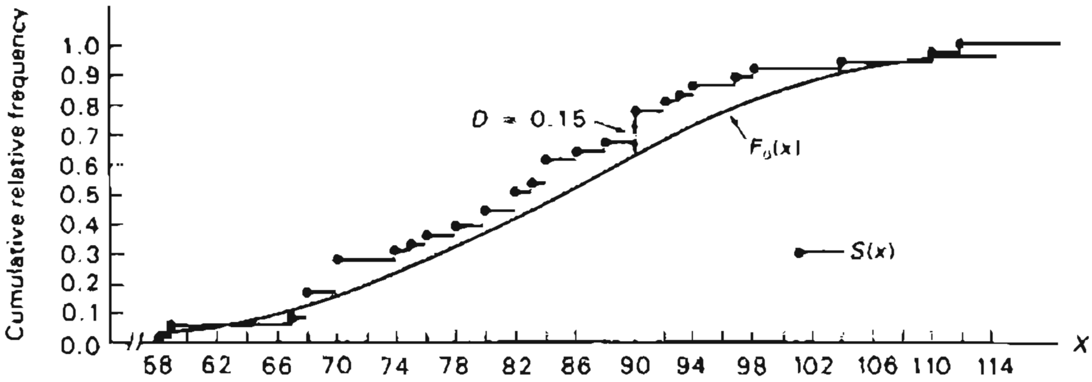


Figure 4.8: $S(x)$, $F_0(x)$ and D for fictitious data [Daniel, 1990]

When D is calculated arithmetically, it is not always sufficient to calculate and choose from the possible values of $|S(x) - F_0(x)|$. As $S(x)$ is a step function, the largest vertical distance between $S(x)$ and $F_0(x)$ may not occur at an observed value of x, but at some other value of x [Daniel, 1990]. Figure 4.9 gives a clearer illustration of this statement.

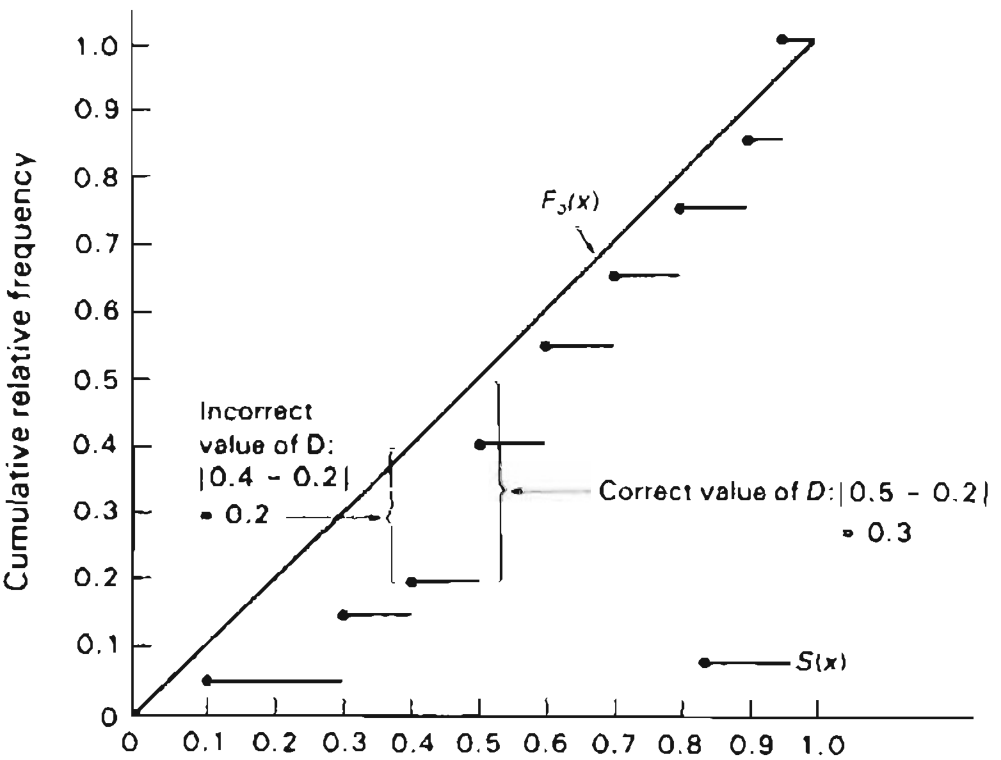


Figure 4.9: Graph of fictitious data showing correct calculation of D [Daniel, 1990]

Hence, the correct value of D may be obtained by calculating the additional differences:

$$|S(x_{i-1}) - F_0(x)| \qquad \textit{for all values of } i = 1, 2, \ldots, r+1$$

where: r = the number of different values of x, and $S(x_0) = 0$ [Daniel, 1990].

The correct value of the test statistic for the KS test is then [Daniel, 1990]:

$$D = \max_{1 \le i \le r} \left\{ \max\left(\left| S(x_i) - F_0(x_i) \right|, \left| S(x_{i-1}) - F_0(x_i) \right| \right) \right\} \tag{4.19}$$

Goodness-of-fit test statistics do not provide a true probability measure for the data actually coming from the hypothesised distribution. Instead, they estimate the probability that random data generated from the hypothesised distribution would produce a goodness-of-fit test statistic value as low as that calculated from the observed data [Conover, 1980].

4.3.3 Lilliefors goodness-of-fit test

When the parameters of the hypothesised distribution must be estimated from the sample data, rather than specified in advance, the Kolmogorov-Smirnov one-sample test no longer applies in the strict sense [Daniel, 1990]. A related nonparametric goodness-of-fit test, the Lilliefors test may be employed when the *mean* μ and/or the *variance* σ^2 of the hypothesised population distribution need to be estimated from the sample data. The test statistic for the Lilliefors test is identical to the test statistic for the Kolmogorov-Smirnov one-sample test, i.e.:

$$D = \max_{1 \le i \le r} \left\{ \max\left(\left| S(x_i) - F_0(x_i) \right|, \left| S(x_{i-1}) - F_0(x_i) \right| \right) \right\} \tag{4.20}$$

Compared to the KS test, the only procedural change is that a separate table is consulted for the critical value of the test statistic, depending on whether the *mean* μ only, the *variance* σ^2 only, or both μ *and* σ^2 of the hypothesised population distribution need to be estimated from the sample data [Daniel, 1990].

4.3.4 Application of Lilliefors test to Monte Carlo simulation results

The Lilliefors test was utilised to establish whether the Monte Carlo simulated *Dangerous Goods Accident Rate* and *Dangerous Goods Releasing Accident Rate* at the Edwin Swales VC Drive – South Coast Road intersection follow a Lognormal distribution.

In Section 4.3.1 a graphical comparison was made of: the empirical cumulative distribution function of *ln[Dangerous Goods accidents/year]*, $S(x)$; and the cumulative distribution function, $F_0(x)$, of a hypothesised Normal distribution, with parameters *mean* $\mu = 1.85$ and *standard deviation* $\sigma = 0.27$ (which were estimated from the sample data of *ln[Dangerous Goods accidents/year]*). The results of this comparison are reproduced in Figure 4.10.

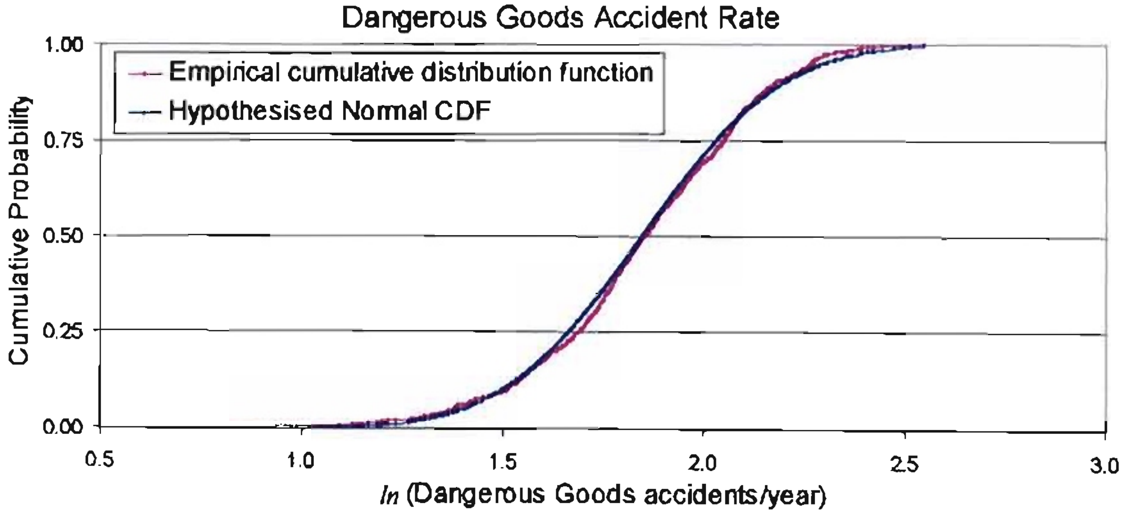


Figure 4.10: Comparison of: the empirical cumulative distribution function of *ln[Dangerous Goods accidents/year]*, $S(x)$; and the cumulative distribution function of the hypothesised Normal distribution, $F_0(x)$, Edwin Swales VC Drive – South Coast Road intersection

In the limit, the critical value of the Lilliefors test statistic at the $\alpha = 0.05$ level of significance, when both μ *and* σ^2 are estimated, is calculated as:

$$Critical\ Value = {}^{0.895}\!/_{d_n} \qquad (4.21)$$

where:

$$d_n = \left(\sqrt{n} - 0.01 + 0.83/\sqrt{n}\right) \tag{4.22}$$

n = the total number of sample observations [Daniel, 1990]

From Equations (4.21) and (4.22): The critical value of the Lilliefors test statistic decreases, as n, the total number of sample observations, increases.

The Monte Carlo simulation consisted of one thousand independent recalculations of the stochastic model. Hence, n = 1000. Substituting into Equations (4.21) and (4.22), yields:

Critical Value of the Lilliefors test statistic = 0.0283 (at the α = 0.05 level of significance)

The test statistic for the Lilliefors test, D is the greatest vertical distance between $S(x)$ and $F_0(x)$ in Figure 4.10. D was calculated arithmetically in Microsoft Excel™ using Equation (4.19). A summary of the Lilliefors test follows:

Null hypothesis: *ln[Dangerous Goods accidents/year]* follows a Normal distribution

Test statistic calculated for the Lilliefors test, D = 0.0355

Critical value of the Lilliefors test statistic = 0.0283

Test result: Reject the hypothesis of normality at the α = 0.05 level of significance, as D >*Critical Value*

As the natural logarithms of *Dangerous Goods accidents/year* are not Normally distributed, the hypothesis that the *Dangerous Goods Accident Rate* is Lognormally distributed, is rejected at the α = 0.05 level of significance.

In Section 4.3.1, a graphical comparison was also made of: the empirical cumulative distribution function of *ln[Years/Releasing Dangerous Goods Accident]*, $S(x)$; and the cumulative distribution function, $F_0(x)$, of a hypothesised Normal distribution, with parameters *mean* μ = *-0.11* and *standard deviation* σ = *0.66* (which were estimated from the sample data of *ln[Years/Releasing Dangerous Goods Accident]*). The results of this comparison are reproduced in Figure 4.11.

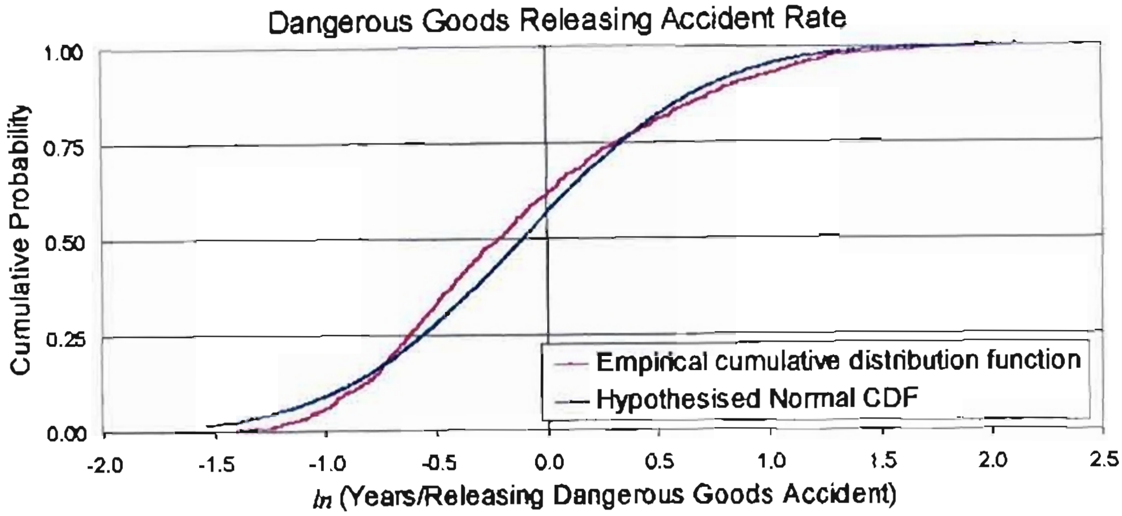


Figure 4.11: Comparison of the empirical cumulative distribution function of *ln[Years/Releasing Dangerous Goods Accident]*, *S(x)*; and the cumulative distribution function of a hypothesised Normal distribution, $F_0(x)$, Edwin Swales VC Drive – South Coast Road intersection

The test statistic for the Lilliefors test, *D* is the greatest vertical distance between *S(x)* and $F_0(x)$ in Figure 4.11. *D* was calculated arithmetically in Microsoft Excel™ using Equation (4.19). A summary of the Lilliefors test follows:

> **Null hypothesis**: *ln[Years/Releasing Dangerous Goods Accident]* follows a Normal distribution
>
> **Test statistic** calculated for the Lilliefors test, $D = 0.0763$
>
> **Critical value** of the Lilliefors test statistic = 0.0283
>
> **Test result**: Reject the hypothesis of normality at the $\alpha = 0.05$ level of significance, as $D >$ *Critical Value*

As the natural logarithms of *Years/Releasing Dangerous Goods Accident* are not Normally distributed, the hypothesis that the *Dangerous Goods Releasing Accident Rate* is Lognormally distributed, is rejected at the $\alpha = 0.05$ level of significance.

The critical value of the Lilliefors test statistic at the $\alpha = 0.01$ significance level, when both μ and σ^2 are estimated, is calculated as:

$$Critical\ Value = {1.035}/{d_n} = 0.0327 \qquad (4.23)$$

when n = 1000 [Daniel, 1990]. Hence, even at the α = 0.01 level of significance, the hypothesis of Lognormality is rejected for both the *Dangerous Goods Accident Rate* and *Dangerous Goods Releasing Accident Rate.*

Conover [1980] asserted that real data are never truly distributed according to any distribution known to man and that almost any goodness-of-fit test would result in rejection of the null hypothesis if the number of observations was very large. The Central Limit Theorem states that the product of a series of random variables tends *in the limit* to be Lognormal in character, regardless of the distributions from which the input variables arise [Benjamin & Cornell, 1970]. With this in mind, the following experiment was undertaken:

A series of Normal random variables, all with the same *mean* μ and *standard deviation* σ, was multiplied and the distribution of the result (the *product*) was tested for goodness-of-fit to a Lognormal distribution. The *product* consisted of an array of one thousand values. The approach used to test the *Dangerous Goods Accident Rate* and *Dangerous Goods Releasing Accident Rate* for Lognormality, was again utilised. Over the course of the experiment, the number of Normal random variables that constituted the *product* was gradually increased. Even when a series of ten Normal random variables was multiplied, the natural logarithms of the *product* did not consistently pass the Lilliefors test for Normality at the α = 0.05 level of significance.

Hence, though they are tending towards the Lognormal, it is unsurprising that the distributions of the *Dangerous Goods Accident Rate* and *Dangerous Goods Releasing Accident Rate* (parameters which are comprised of only two and three random variables, respectively) did not pass the goodness-of-fit test.

4.4 Sensitivity Analysis

The danger exists that the proposed model for estimating dangerous goods accident and release rates has been oversimplified and that some important details of the real situation, which would significantly alter the results, have been omitted from the model. In applied analytical work, variations of the model need to be considered; where each new variation is an attempt to add another fact of the real world into the model, or to revise some of the simplifying assumptions that have been made. The process of analysing different variations of the model, to observe how they may affect the results, is called sensitivity analysis [Pet-Armacost et al. 1999].

4.4.1 Tornado diagrams

Tornado-style sensitivity-analysis diagrams depict the significance of each of the input parameters and consequently, reveal which input parameter has the greatest effect on the model output. Tornado diagrams are generated by recording the value of the output parameter, as the input parameters are changed, one at a time, from a given lower bound, to a given best estimate, to a given upper bound [Pet-Armacost et al. 1999].

In fact, a sensitivity analysis conducted earlier in this investigation revealed that variations in the value of the *Exposure* input parameter (measured in units of Entering Heavy vehicles/year) were having no effect on the estimated *Dangerous Goods Accident Rate* and *Dangerous Goods Releasing Accident Rate*. This indicated to the researcher that the specific manner in which the deterministic model had been formulated, had resulted in the Exposure term being "cancelled out".

4.4.2 Input parameter settings

Table 4.10 presents the range of values of the input parameters that were used in a sensitivity analysis of the proposed model for estimating dangerous goods accident and release rates.

Table 4.10: Input parameter settings used in a sensitivity analysis of the *Dangerous Goods Accident Rate* and the *Dangerous Goods Releasing Accident Rate*, Edwin Swales VC Drive – South Coast Road intersection

Input Parameters	Best estimate	Lower bound	Upper bound
Heavy-vehicle Accident Rate	99	81	119
% of Heavy vehicles transporting dangerous goods	6.67%	3.61%	9.73%
Probability of release | Dangerous Goods accident	0.140	0.035	0.375

The selection of the input parameter settings reported in Table 4.10, is detailed in the following section. .

- **Heavy-vehicle Accident Rate**

As discussed in Section 4.2.2, the decision was taken to model the *Heavy-vehicle Accident Rate* at the Edwin Swales VC Drive – South Coast Road intersection, as a Poisson random variable with *mean* $\lambda = 99$ Heavy-vehicle accidents/year. An array of one thousand Poisson random variables with *mean* $\lambda = 99$ was generated and analysed statistically. The 2.5 and 97.5 percentile levels of this array were chosen as the lower bound and upper bound, respectively of the *Heavy-vehicle Accident Rate*. Thus, 95 per-cent of these simulated values were incorporated into the sensitivity analysis.

- **Proportion of heavy vehicles transporting dangerous goods**

As discussed in Section 4.2.3, the decision was taken to model the proportion of heavy vehicles transporting dangerous goods at the Edwin Swales VC Drive – South Coast Road intersection, as a Normal random variable with *mean* $\mu = 0.0667$ and *standard deviation* $\sigma = 0.0156$. The lower and upper bounds of the *Proportion of heavy vehicles transporting dangerous goods*, for use in the sensitivity analysis, were calculated using the formula: $\mu \pm 1.96\sigma$. The value 1.96 represents the 97.5th percentile of the standard normal distribution; hence, for data that follow a Normal distribution, 95 per-cent of the values will be within a multiple of 1.96 standard deviations of the mean [Daniel, 1990]. For the purpose of brevity, proportions have been converted to percentages in Table 4.10.

- **Probability of release given a dangerous goods accident**

The input parameter settings for the *Probability of release given an accident involving a dangerous goods vehicle* were based on the information presented in Section 4.2.4

4.4.3 Results of the sensitivity analysis

A tornado-style sensitivity-analysis diagram, depicting the effect of the input parameters on the *Dangerous Goods Accident Rate* is presented in Figure 4.12.

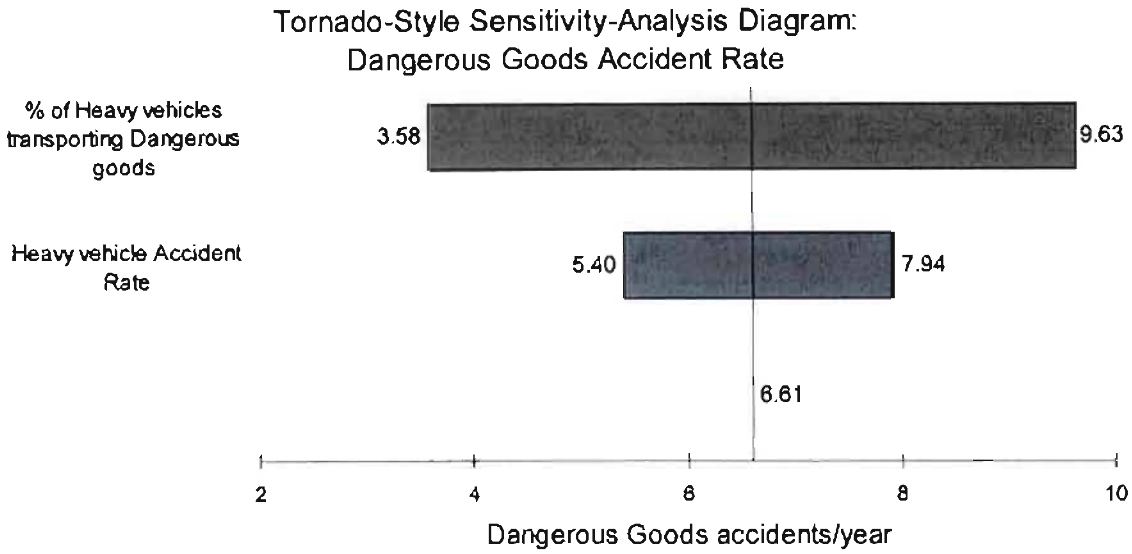


Figure 4.12: Sensitivity analysis of the input parameters on the *Dangerous Goods Accident Rate*, Edwin Swales VC Drive – South Coast Road intersection

- **Guidance on interpreting Figure 4.12**

The first bar in Figure 4.12 may be read as follows: As the *Percentage of heavy vehicles transporting dangerous goods* is increased (from 3.61 per-cent to 9.73 per-cent), while keeping the *Heavy-vehicle Accident Rate* constant (at 99 Heavy vehicle accidents/year); the *Dangerous Goods Accident Rate* increases from 3.58 to 9.63 Dangerous Goods accidents/year.

The *Dangerous Goods Accident Rate* calculated using the "best estimate" of the input parameters from Table 4.10 (6.61 Dangerous Goods accidents/year) is indicated by the value at which the vertical axis intersects the horizontal axis.

Figure 4.12 illustrates that at the Edwin Swales VC Drive – South Coast Road intersection, the expected variation in the *Proportion of heavy vehicles transporting dangerous goods* has a more significant effect on the *Dangerous Goods Accident Rate* than the expected variation in the *Heavy-vehicle Accident Rate.*

A tornado-style sensitivity-analysis diagram depicting the effect of the input parameters on the *Dangerous Goods Releasing Accident Rate* is presented in Figure 4.13.

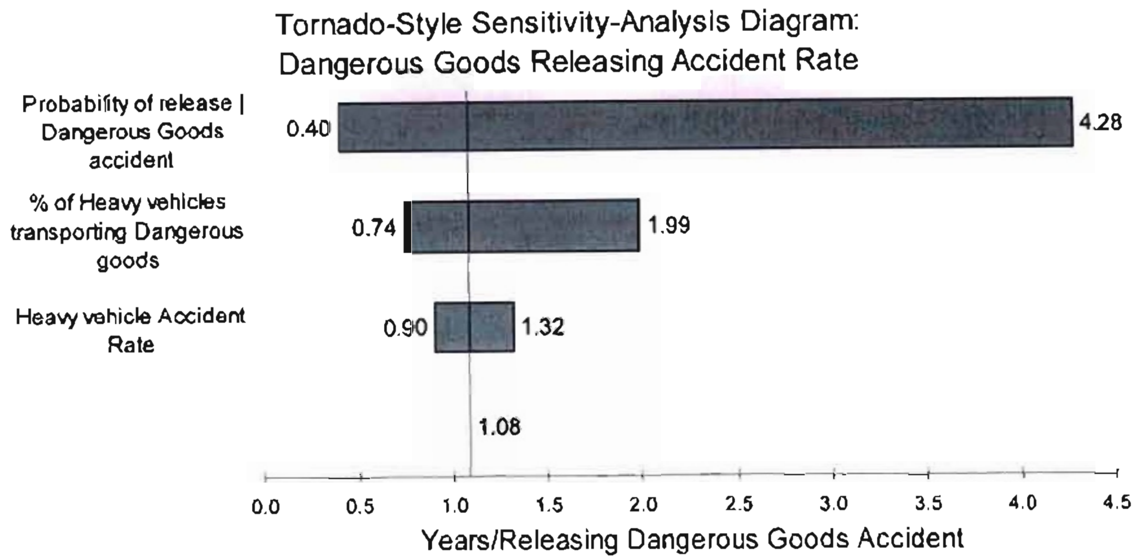


Figure 4.13: Sensitivity analysis of the input parameters on the *Dangerous Goods Releasing Accident Rate*, Edwin Swales VC Drive – South Coast Road intersection

Figure 4.13 illustrates that, in comparison to the expected variation in the other input parameters, the expected variation in the *Probability of release given a dangerous goods accident* has the most significant effect on the *Dangerous Goods Releasing Accident Rate* at the Edwin Swales VC Drive – South Coast Road intersection.

4.5 Chapter Summary

Two methods for estimating the dangerous goods accident and release rates at intersections have been developed: a deterministic approach and the stochastic approach based on Monte Carlo simulation. The deterministic approach revealed that the Edwin Swales VC Drive – South Coast Road intersection has the highest expected rate of dangerous goods accidents and releases, followed by the Bayhead Road – South Coast Road intersection. The Edwin Swales VC Drive – South Coast Road intersection is expected to experience, on average: six dangerous goods accidents per year and one releasing dangerous goods accident every thirteen months. The Tara Road – Duranta Road, M4 Southern Freeway – Duranta Road and The Avenue East – Refinery Drive intersections have a comparatively lower expected *Dangerous Goods Accident Rate* and *Dangerous Goods Releasing Accident Rate*. No reliable South African dangerous goods incident statistics are available to validate these results.

Acrylonitrile, Anhydrous Hydrogen Fluoride, Benzene, Isopropylamine, Methyl Isocyanate and Tetra Ethyl Lead, the Danger group I substances that are being transported through the selected intersections, present a very severe risk. However, as the proportion of heavy vehicles transporting these substances is low (compared to Petroleum for example), the estimated frequency of accidents and releases involving Danger group I substances is much lower.

At the Edwin Swales VC Drive – South Coast Road intersection, the mean values of the *Dangerous Goods Accident Rate* and the *Dangerous Goods Releasing Accident Rate* estimated using Monte Carlo simulation, are quite similar to those results estimated using the deterministic approach. However, in comparison to the deterministic models typically used in transportation risk assessments, Monte Carlo simulation enables a more detailed understanding of the nature and distribution of dangerous goods accident and releases. Utilising the same raw data as a deterministic approach, coupled with reasonable assumptions based on the available data; Monte Carlo simulation provides the researcher with far more information.

On the basis of the Central Limit Theorem and further visual observations, the hypothesis that the Monte Carlo simulated *Dangerous Goods Accident Rate* and *Dangerous Goods Releasing Accident Rate*, follow a Lognormal distribution, was investigated using the Lilliefors test. Although they are "tending towards" the Lognormal, the distributions of the *Dangerous Goods Accident Rate* and *Dangerous Goods Releasing Accident Rate* at the Edwin Swales VC Drive – South Coast Road intersection did not pass the goodness-of-fit test. A sensitivity-analysis was used to investigate the significance of each of the input parameters of the proposed model for estimating dangerous goods accident and release rates. At the Edwin Swales VC Drive – South Coast Road intersection, the expected variation in the *Proportion of heavy vehicles transporting dangerous goods* had a more significant effect on the *Dangerous Goods Accident Rate* than the expected variation in the *Heavy-vehicle Accident Rate*. In comparison to expected variation in the *Proportion of heavy vehicles transporting dangerous goods* and the *Heavy-vehicle Accident Rate*, the expected variation in the *Probability of release given a dangerous goods accident* had the most significant effect on the *Dangerous Goods Releasing Accident Rate*.

This chapter has verified that, with the use of Monte Carlo simulation, dangerous goods transportation risk assessments may be performed even when there are substantial data uncertainties. The formulation and analysis of a Monte Carlo simulation in

Microsoft Excel™, is preferable to using a commercial Monte Carlo simulation package and a program like SPSS™ or MATLAB™ for subsequent statistical analysis of the simulation results. In addition to the substantial cost savings, a deeper understanding of the system being modelled is achieved and the "black box" effect may be largely avoided. As the researcher is more familiar with the underlying assumptions and restrictions, the hazard of "stretching" the techniques and models beyond their limits of credibility is reduced.

CHAPTER 5

5. CONSEQUENCES OF DANGEROUS GOODS RELEASES

This chapter describes the methodology utilised to estimate the consequences of dangerous goods releases at intersections. Various tools are employed in this consequence assessment, including dispersion modelling and geographical information systems. The impacts to road users are investigated using queuing analysis. A brief overview of the factors affecting the dispersion potential of the atmosphere is also provided.

5.1 Overview of Dispersion Modelling

The dangerous goods of interest to this investigation are those that could give rise to dispersing vapour clouds upon release. These could subsequently cause harm through inhalation or absorption through the skin. When a release of dangerous goods occurs, a dispersion model may be utilised to estimate the size, shape and direction of movement of the plume resulting from the spill [CERC, 2001].

Accidental releases may result in high short-term ground-level concentrations of contaminants. Dispersion modelling may be used to:

- Investigate the effects of different accidental release scenarios
- Identify the types of accidental releases which could result in significant downwind adverse effects
- Identify potentially affected people in the event of an accidental release, and to plan an appropriate response strategy [NIWAR, 2002].

An atmospheric dispersion model is a mathematical simulation of the physics governing the transport and dispersion of contaminants in the atmosphere. Most modern dispersion models are computer programs that estimate the contaminant concentration downwind of a source using information on the contaminant emission rate, characteristics of the emission source, local topography and meteorology of the area. The process of dispersion modelling contains four stages (data input, dispersion calculations, deriving the concentrations and data analysis) [NIWAR, 2002]. Figure 5.1 presents an overview of the dispersion modelling process.

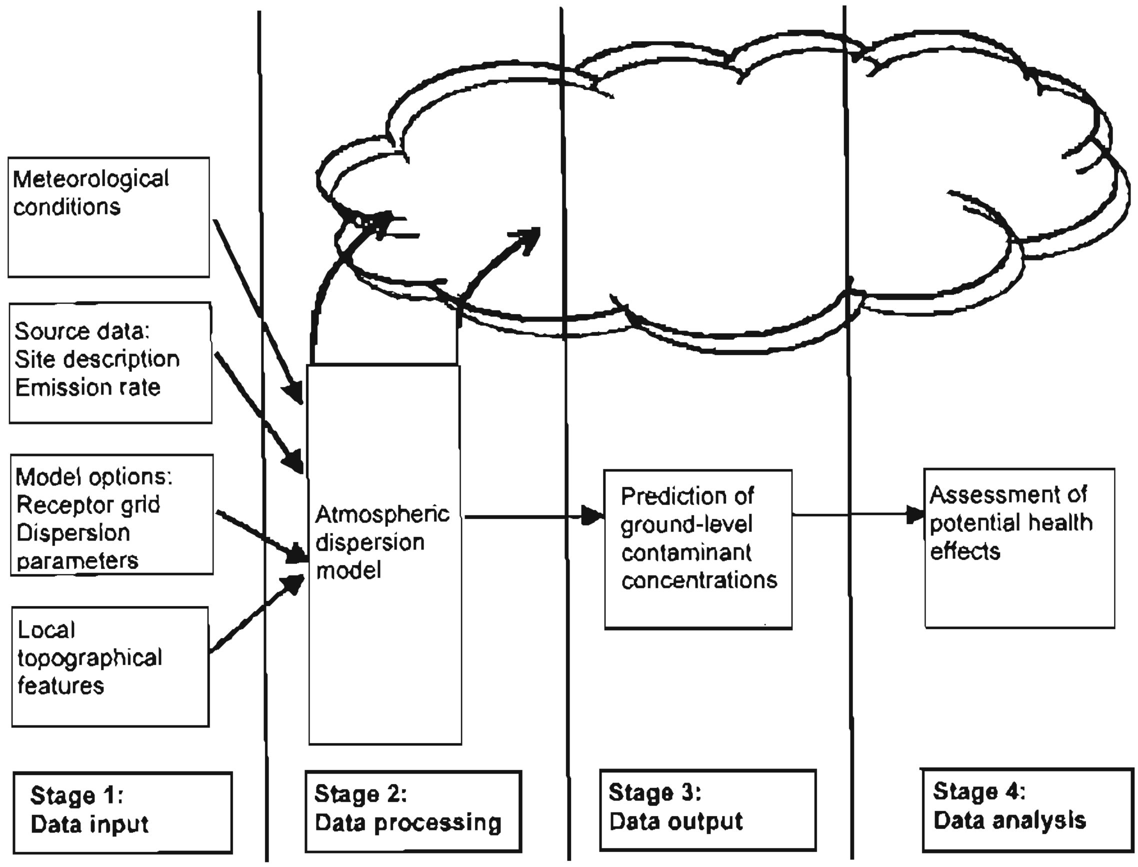


Figure 5.1: Summary of the dispersion modelling process [after NIWAR, 2002]

5.2 Dispersion Potential of the Atmosphere

Meteorological processes govern the dispersion and ultimate removal of contaminants from the atmosphere. Dispersion is composed of vertical and horizontal components. The stability of the atmosphere and the depth of the atmospheric boundary layer define the vertical component of dispersion. The horizontal component of dispersion is chiefly a function of the wind field [Driedonks, 1982].

5.2.1 Stability and instability

The atmosphere is said to be stable when a mass of air, uplifted by some outside force, tends to return to its original position. The atmosphere is said to be unstable when a mass of air, which is given an upward or downward displacement, continues to rise or sink of its own accord. Orographic lifting may trigger this instability, as the air parcel travels over a mountain (Figure 5.2b) [Preston-Whyte & Tyson, 1988].

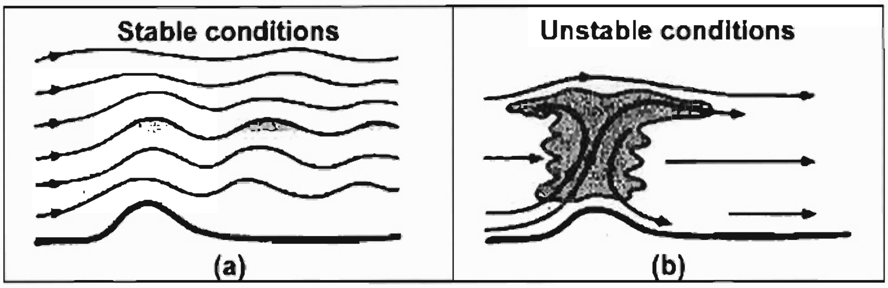


Figure 5.2: Vertical motion and cloud occurrence under stable and unstable conditions [after Preston-Whyte & Tyson, 1988]

The variation of temperature with height is referred to as the *lapse rate*. A particle of unsaturated air (i.e. relative humidity less than 100 per-cent) undergoing vertical motion warms or cools at the *Dry Adiabatic Lapse Rate* (DALR). An adiabatic process is one in which no heat enters or leaves the system. If temperature decreases with height, a *lapse* condition is said to prevail. If temperature (T) increases with height (z), a *temperature inversion* is said to prevail. If there is no variation of temperature with height, *isothermal* conditions are said to prevail. Figure 5.3 illustrates the different types of lapse rates. Inversions and isothermal conditions are stable. Lapse conditions may be stable or unstable depending on the magnitude of the *Environmental Lapse Rate* (ELR) [Preston-Whyte & Tyson, 1988].

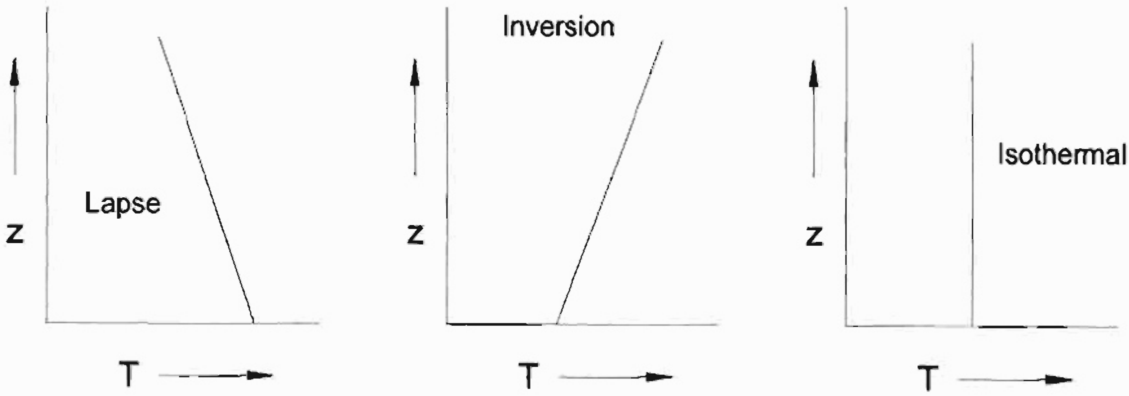


Figure 5.3: Types of lapse rates [after Preston-Whyte & Tyson, 1988]

If the Environmental Lapse Rate is less than the Dry Adiabatic Lapse Rate, the air is stable (Figure 5.4a). Let *Tp* be the temperature of a parcel of air and *Ta* be the temperature of the ambient air. A parcel of air at a height z_0, lifted by some external force will cool at the dry adiabatic lapse rate. At the new height z_1, the air parcel will be cooler and denser than the surrounding air; hence, it will sink back to its original position under the action of the buoyancy force. If the air parcel is forced downward, it will warm at the dry adiabatic lapse rate. At the new height z_2, the air parcel will be warmer and less dense than the environmental air; hence, the positive buoyancy of the parcel will cause it to rise back to its original position [Preston-Whyte & Tyson, 1988].

If the ELR is greater than the DALR, the air is unstable (Figure 5.4b). A parcel of air at a height z_0, lifted by some external force will cool at the DALR. At the new height z_1, the air parcel will be warmer and less dense than the environmental air; hence, it will continue to rise under the action of the buoyancy force. If the parcel is forced downward, it will warm at the DALR. At the new height z_2, the air parcel will be cooler and denser than the environmental air; it will continue to sink under the action of the buoyancy force [Preston-Whyte & Tyson, 1988].

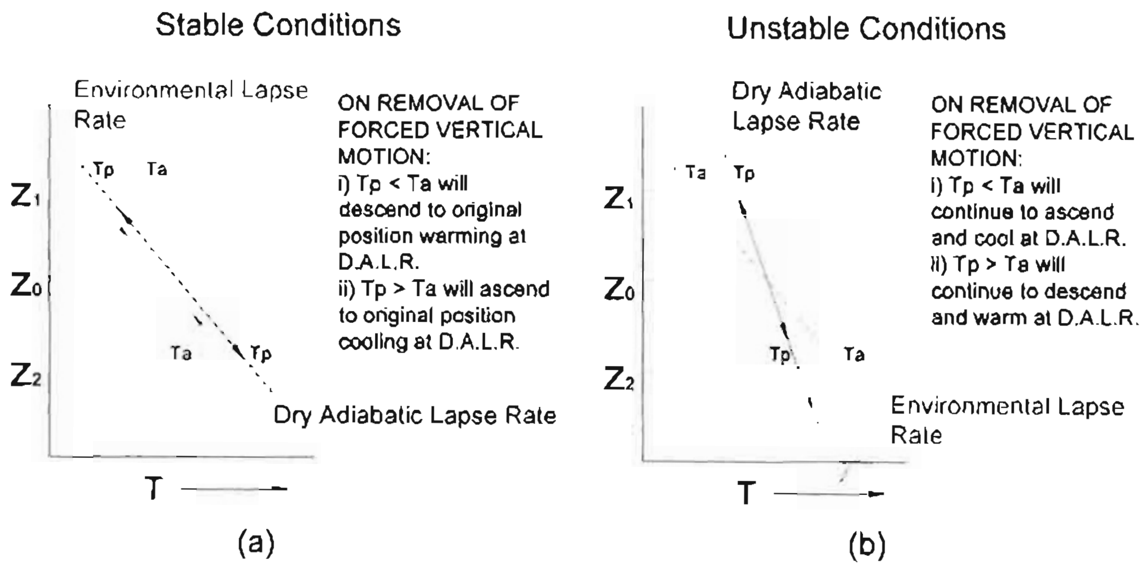


Figure 5.4: The definition of stability and instability in the atmosphere [after Preston-Whyte & Tyson, 1988]

When the ELR is equal to the DALR, a condition of neutral stability is said to prevail and vertical motion is neither resisted nor assisted. The atmosphere is continually changing between neutral, unstable and stable conditions. Unstable conditions favour the dispersion of atmospheric contaminants. Unstable conditions are frequently experienced during sunny, summer days. Dispersion and mixing are suppressed under stable conditions; thus, ground level releases may remain concentrated for long distances from the source. Stable conditions may occur as a result of surface inversions. Surface inversions are often characteristic of clear, calm and dry winter nights [Preston-Whyte & Tyson, 1988].

5.2.2 Atmospheric boundary layer

The atmospheric boundary layer is often called the mixing layer as it represents the vertical extent to which contaminants can be mixed in the atmosphere. Motion in the atmosphere can be resolved into a fluctuating component superimposed on a general mean flow [Pasquill & Smith, 1983]. The fluctuating components of atmospheric flow are referred to as eddies or turbulence. Turbulence is responsible for vertical fluxes of heat, matter and momentum. Eddies occur at varying time and space scales, with larger eddies continuously breaking down into smaller eddies. During the day, vigorous small-scale eddies are generated by heating and the boundary layer may extend to a depth of several hundred metres. At night, the development of highly stable air near the ground suppresses turbulence and mixing. This decreases the depth of the mixing layer [Preston-Whyte & Tyson, 1988]. Turbulent mixing forms and maintains the atmospheric boundary layer. The production mechanisms for turbulent mixing are: convectively generated turbulence produced by surface heating, mechanical turbulence produced by surface friction and finally, mechanical turbulence produced by local wind shear at the top of the boundary layer, which is a weak source of turbulence [Driedonks, 1982].

The daytime convective mixing layer ranges in depth from five hundred metres to two kilometres. The depth of the nocturnal boundary layer varies from tens of metres to a few hundred metres. Thus, in the course of one diurnal cycle, the atmospheric boundary layer exists in two states. The first is a deep, convectively driven, turbulent mixing layer during the daytime; the second is a shallower layer of shear-driven turbulence with a surface-based temperature inversion at night. Shortly after sunrise the boundary layer is not yet in a state of fully developed convection. The mixing layer grows slowly because the nocturnal inversion has to be eroded and the heat input is still not very large. After the nocturnal inversion has been eroded the mixing layer grows quickly [Driedonks, 1982].

5.2.3 Winds

The wind speed affects the distance to which contaminants will be transported downwind. The variability in wind direction controls the extent of crosswind spreading of contaminants. Winds combine with surface roughness to generate mechanical turbulence in the atmospheric boundary layer [US-EPA, 1998].

Wind roses display the joint frequency distributions of wind speed and wind direction. The frequencies of wind speeds for each direction are depicted within wind speed classes, which are assigned high and low bounds (much like bins in a histogram). The joint frequency distribution is portrayed as a *rose*, made up of *petals* oriented along each direction radiating from a central circle. Each petal is made up of rectangular segments with variable widths and lengths representing the actual frequency of the direction/class combination. Thin dashed concentric circles are drawn at fixed percentage intervals (usually 5 per-cent) for easier visual interpretation of petal lengths. The frequency of calms is indicated in the central circle. Calm periods are periods for which wind speeds are below one metre-per-second (m/s) [Lakes Environmental Software, 2000]. The South African Weather Service provided meteorological data for use in this investigation. Figure 5.5 presents the annual average wind rose for the Durban International Airport for the years 1993-2002.

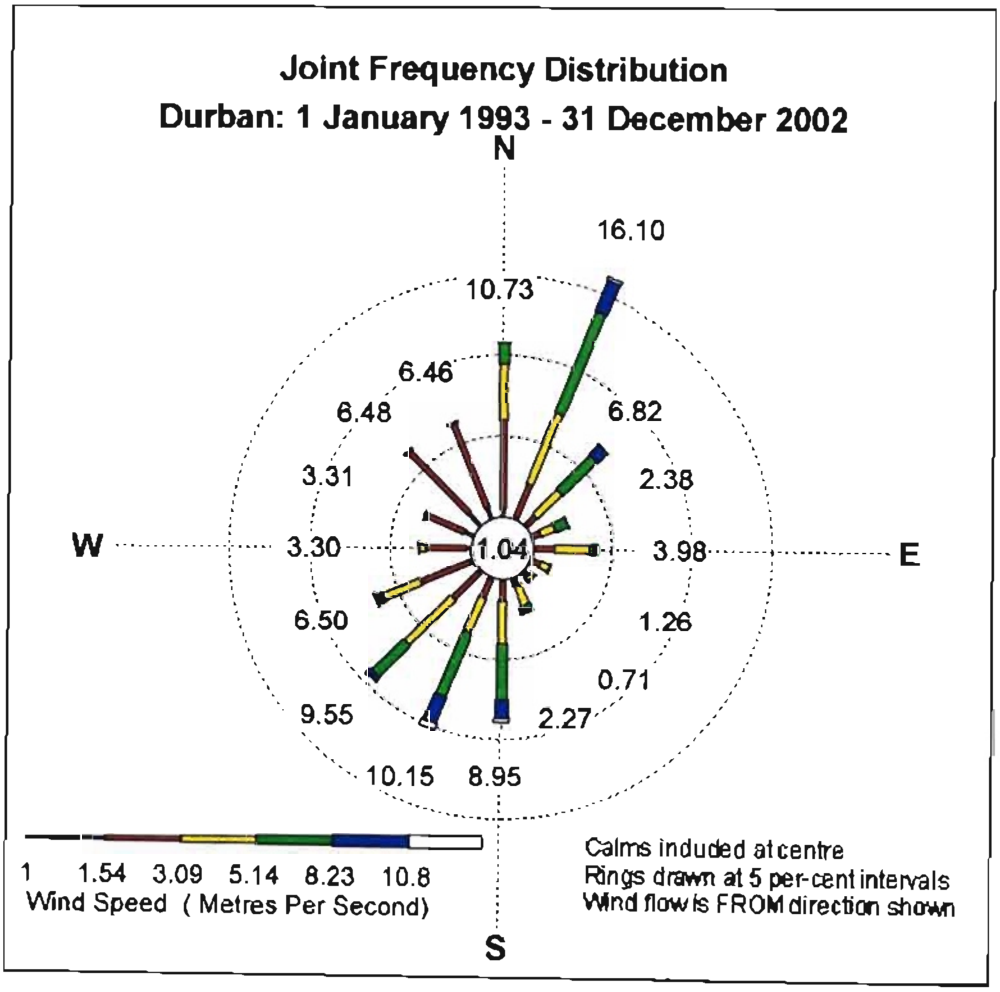


Figure 5.5: Annual average wind rose for the Durban International Airport, 1993-2002

Figure 5.5 illustrates that the predominant winds in the Durban South Basin blow from two sectors: the north, north-northeast and northeast sector; and south, south-southwest and southwest sector, in approximately equal proportions (30 per-cent each). Calm periods prevail for approximately 1 per-cent of the year.

Figure 5.6 illustrates the diurnal variation of the wind field in the Durban South Basin. This variation is partially attributable to land and sea breezes in the region. The differential heating and cooling of land and sea surfaces gives rise to the diurnally reversible land-sea breeze circulation. During the daytime, when sea breezes predominate, high wind speeds and unstable conditions prevail. In contrast, a greater prevalence of calm conditions, weak vertical mixing and stable conditions characterise nights. Land breezes are normally associated with low wind speeds; thus, they do not have a great dispersion potential [Preston-Whyte & Tyson, 1988].

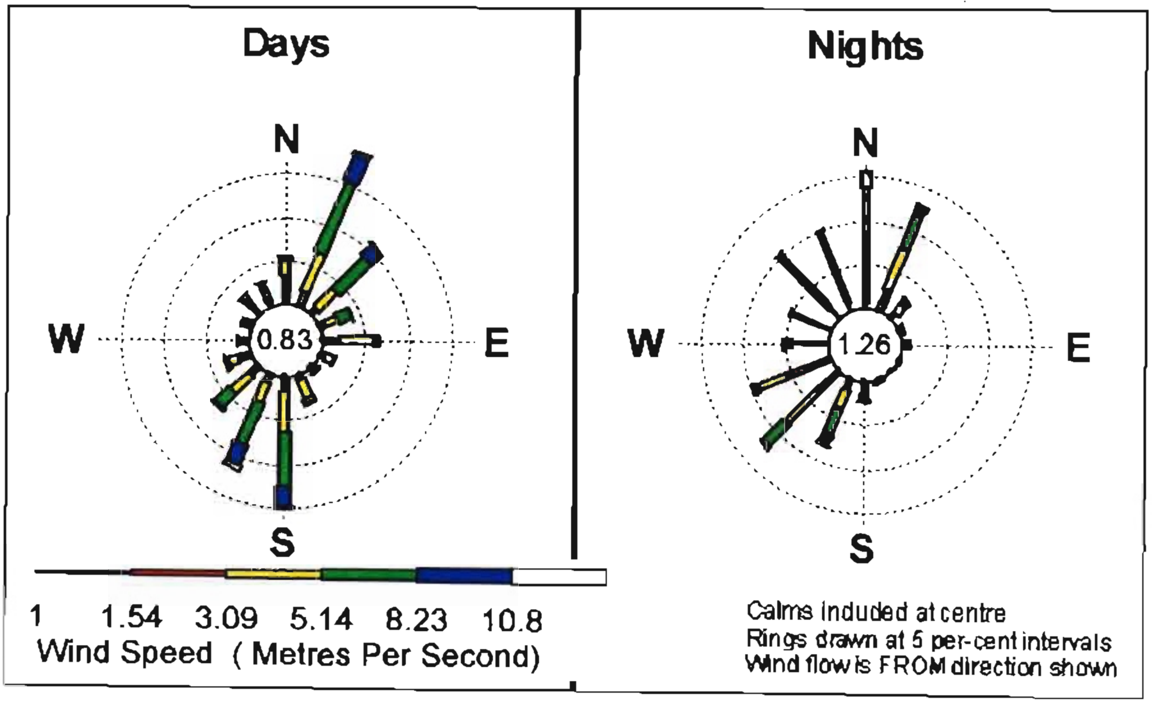


Figure 5.6: Diurnal wind roses for the Durban International Airport, 1993-2002

Figure 5.7 illustrates the seasonal variation in the wind field of the Durban South Basin. Winter nights in particular, experience much lower wind speeds and a greater prevalence of calm conditions [Preston-Whyte & Tyson, 1988]. In preparing the wind roses, summer months were taken as October to March, winter months as April to September.

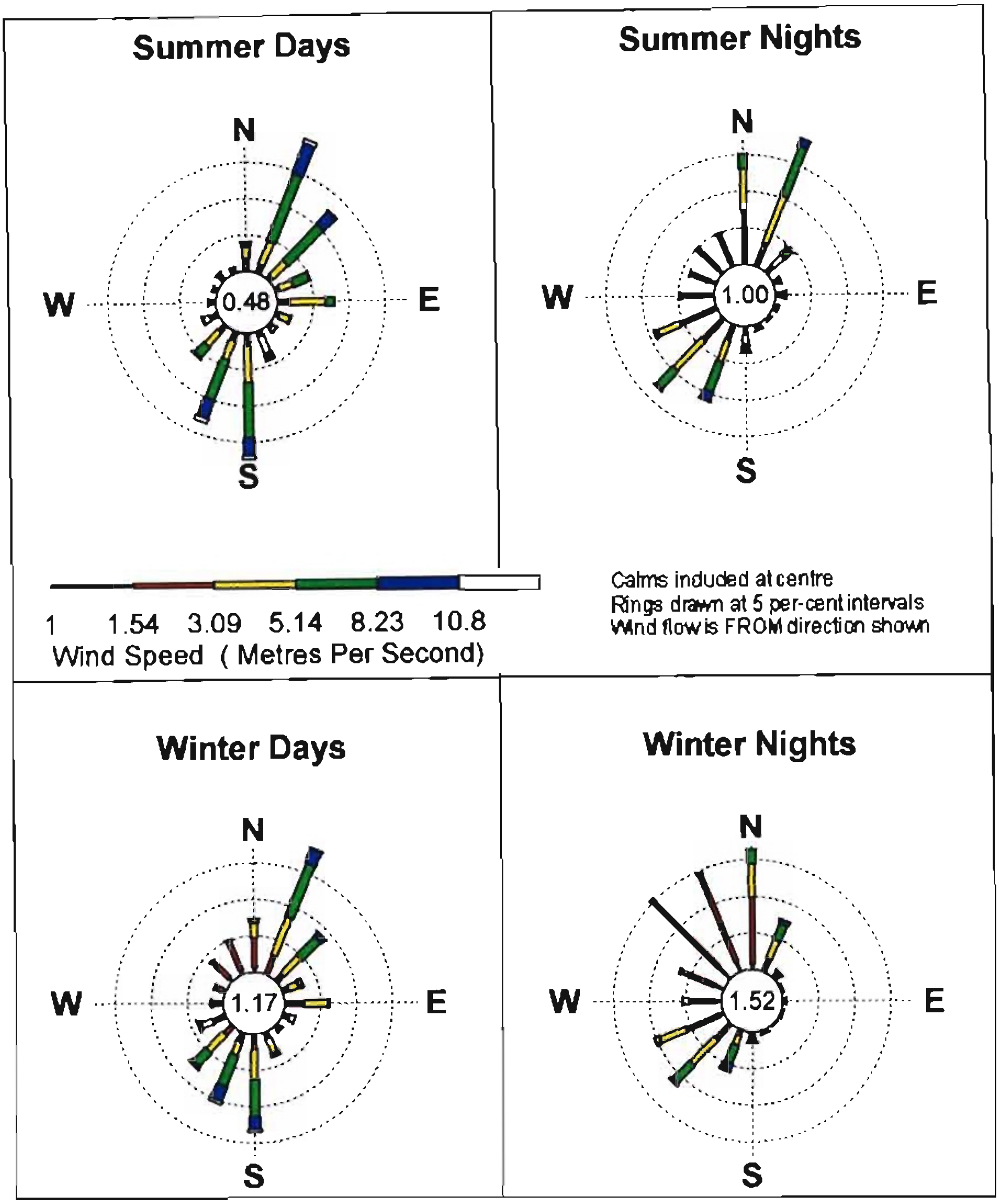


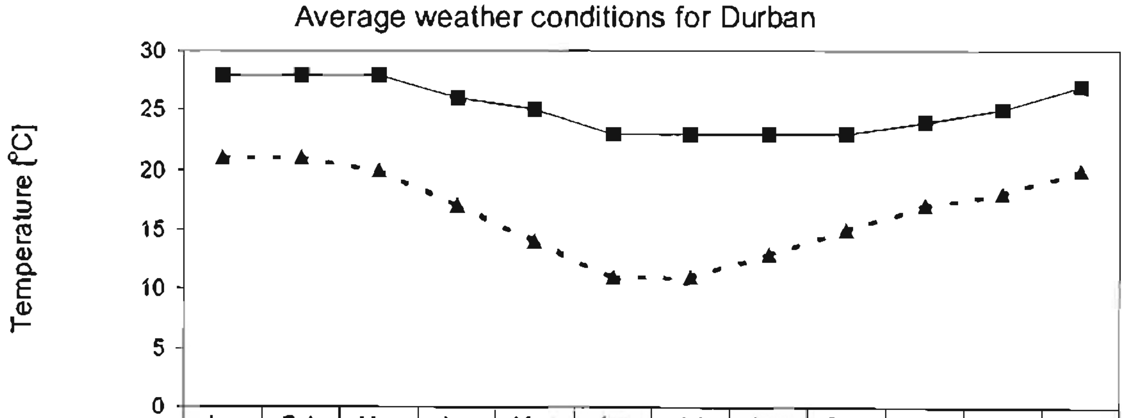
Figure 5.7: Seasonal wind roses for the Durban International Airport, 1993-2002

Wind roses depict graphically the dominant transport direction of the winds for an area. However, due to the influences of local terrain, possible coastal effects, the exposure of the instruments and the variability of the wind, the wind rose statistics may not always be representative of true transport for an area [Lakes Environmental Software, 2000].

5.2.4 Other meteorological parameters

Air temperature and insolation are significant in governing the formation of the mixing and inversions layers. Insolation refers to the amount of electromagnetic energy (solar radiation) incident on the surface of the earth [Pasquill & Smith, 1983]].

There is a relatively low diurnal and seasonal range in air temperature in Durban because of the damping effect of the Indian Ocean [Preston-Whyte & Tyson, 1988]. A summary of the average daily minimum and maximum temperature in Durban for the period 1961–1990, is presented in Figure 5.8.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
—■— Max Temp	28	28	28	26	25	23	23	23	23	24	25	27
- ▲ - Min Temp	21	21	20	17	14	11	11	13	15	17	18	20

Figure 5.8: Diurnal and seasonal variation in temperature in Durban, 1961–1990 [Statistics for Durban, 2001]

Due to cloudy weather during the summer months, Durban experiences a sunshine duration of approximately 45 per-cent during daylight hours. In contrast, insolation durations of approximately 70 per-cent occur during winter months [Hunter, 1990; Statistics for Durban, 2001].

5.2.5 Pasquill stability categories

Pasquill & Smith [1983] placed the stability of the atmosphere into six categories (*A-F*) in terms of wind speed, the time of year, time of day or night and the degree of cloud cover. Category *A* represents very unstable conditions; category *F* represents very stable conditions. These categories are presented in Table 5.1.

Table 5.1: Pasquill stability categories in terms of wind speed, insolation and state of sky [after Pasquill & Smith, 1983]

Surface wind speed [m/s]	Insolation			Night	
	Strong	Moderate	Slight	Thinly overcast/ ≥ ⁴/₈ low cloud	≤ ³/₈ cloud
< 2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

5.2.6 Parameterisation of the boundary layer

A more recent method of describing the condition of the boundary layer is to use a boundary layer scaling approach. This approach characterises the boundary layer in terms of two parameters, the boundary layer height (*h*) and the Monin-Ubukhov length (L_{MO}). Many different values of L_{MO} and *h* may correspond to a single Pasquill stability category. Hence, there is no exact correspondence between the boundary layer parameters (*h* and L_{MO}) and the Pasquill stability categories. The parameterisation of the boundary layer allows the inclusion of the variation of boundary layer properties with height [CERC, 2001]. The Monin-Ubukhov length is a measure of the stability of the atmosphere. It is defined as:

$$L_{MO} = \frac{-u_*^{\,3}}{\kappa g F_{\theta_0} / \left(\rho c_p T_0\right)} \tag{5.1}$$

where:

u_* = friction velocity at Earth's surface = $\sqrt{\tau/\rho}$, in m/s

τ = shear stress at Earth's surface, in kg/ms^2

κ = von Karman's constant (= 0.4)

g = acceleration due to gravity, in m/s^2

F_{θ_0} = surface sensible heat flux, in W/m^2

ρ = density of air, in kg/m^3

c_p = specific heat capacity of air, in J/kg/°C

T_0 = near surface temperature, in °C

In stable conditions, the Monin-Ubukhov length is positive. Then, L_{MO} is a measure of the height above which vertical turbulent motion is significantly inhibited by the stable stratification of the air [CERC, 2001]. In unstable or convective conditions, the Monin-Ubukhov length is negative. Then, the magnitude of L_{MO} is a measure of the height above which turbulent motions caused by thermal convection, are more important than the mechanical turbulence generated by friction at the Earth's surface [CERC, 2001]. Figure 5.9 illustrates the different regions of the boundary layer in terms of the parameters h/L_{MO} and z, where z is the height above ground level.

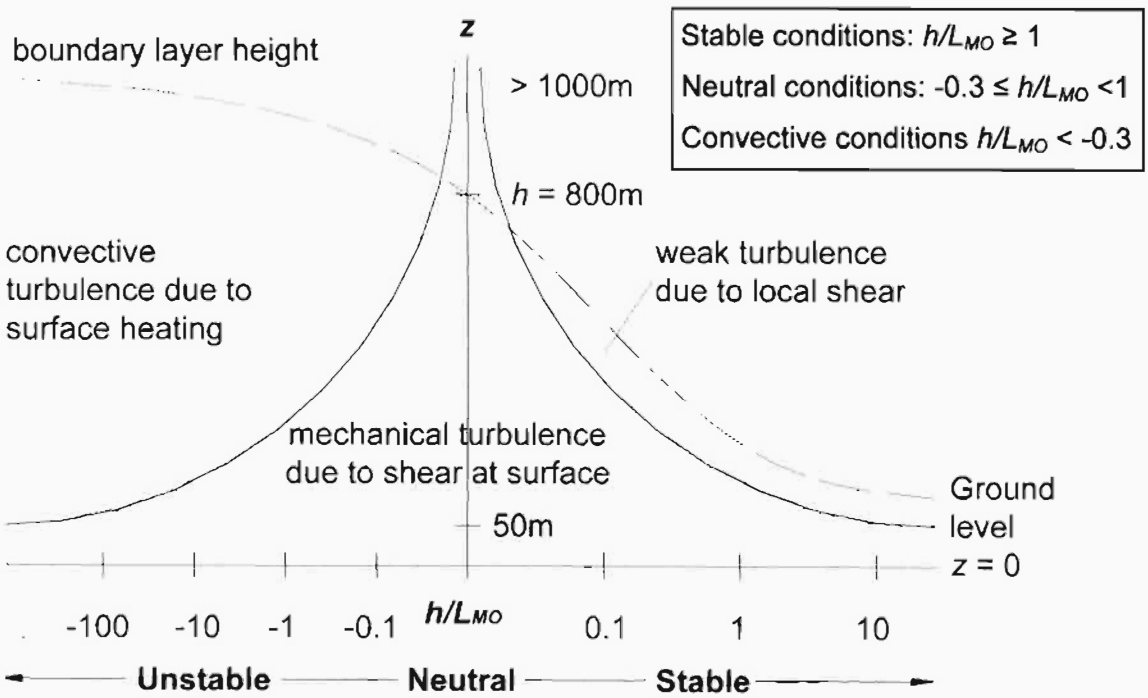


Figure 5.9: Schematic representation of the variation of Monin-Ubukhov length with atmospheric stability [after CERC, 2001]

5.3 Risk Analysis

5.3.1 ADMS™ dispersion model

The dispersion model used in the investigation was *ADMS™* (Advanced Dispersion Modelling System) developed by Cambridge Environmental Research Consultants Ltd. (CERC). ADMS™ is a "new generation" model, which describes the atmospheric boundary layer in terms of two parameters, the boundary layer height (h) and the Monin-Ubukhov length (L_{MO}), instead of a single Pasquill stability category. The

Pasquill stability categories cannot be directly entered into ADMS™ [CERC, 2001]. No general theory or generally accepted semi-empirical expression exists which describes dispersion from a source at all heights within the boundary layer, in all conditions of atmospheric stability and over the full range of distances from the source. ADMS™ uses generally accepted formulae that have been developed for specific ranges of the parameters z/h, h/L_{MO} and x/h (where x refers to downwind distance from the source). ADMS™ then interpolates between these ranges [CERC, 2001].

Different combinations of meteorological input data may be entered in ADMS™, depending on the recorded parameters that are available. Hence, the model is very adaptable. ADMS™ links to other packages such as *Surfer™* (a contour-plotting package produced by Golden Software™) and *Arcview GIS™*, for easy and effective display of results. ADMS™ has been extensively validated [CERC, 2001].

5.3.2 Limitations of ADMS™

ADMS™ is a steady-state dispersion model. The plume formula was derived assuming 'steady-state' conditions, i.e. the formula does not depend on time and is theoretically constant. However, plume characteristics do vary in time, due to changing emissions and meteorological conditions. The term *steady-state* does not mean that conditions are steady from hour to hour [CERC, 2001]. ADMS™ calculates concentrations for each hour from an emission rate and meteorological conditions that are uniform across the modelling domain. Thus, these calculations represent an hourly average of these values. The model is more representative of reality if conditions do not change rapidly within the hour being modelled i.e. conditions are reasonably steady and do not deviate significantly from the average values for the hour being modelled [NIWAR, 2002]. Steady-state models have certain limitations. Those applicable to this investigation are discussed in the following section.

- **Low wind speeds or Calms**

When the wind speed drops below 0.75 m/s, the wind direction becomes irresolvable, and the plume may travel anywhere, or simply pool. The steady-state equations are undefined during low wind speed or calm conditions (wind speed appears on the bottom line of the equations, and cannot be zero). Unfortunately, in many circumstances it is these exact conditions that may lead to the highest ground-level concentrations [NIWAR, 2002]. ADMS™ does not model calm conditions. The model will skip any lines of meteorological data for which the wind speed measured at a height of ten metres is less than 0.75 m/s [CERC, 2001]. Analysis of the meteorological data for the period 1993–2002 revealed that the wind speed was less than 0.75 m/s for just 0.87 per-cent of the record.

- **Spatially uniform meteorological conditions**

Steady-state models assume that the atmosphere is uniform across the entire modelling area and that transport and dispersion conditions exist unchanged long enough for the material to reach the receptor. In the atmosphere, truly uniform conditions rarely occur. Differences in land use, water bodies, surface characteristics and surface moisture produce differences in the structure of the boundary layer that may affect contaminant transport and dispersion. Steady-state dispersion models assume contaminants are transported in a straight line to receptors that may be several hours in transport time away from the source. They take no account of the fact that wind may only be blowing at 1 m/s and will only have travelled 3.6 kilometres in the first hour [NIWAR, 2002].

Despite these limitations, steady-state models provide reasonable results when used appropriately. Even the most sophisticated atmospheric dispersion model cannot predict the precise location, magnitude and timing of ground-level concentrations with total accuracy. Dispersion models are usually subjected to a thorough model evaluation process and the modelling results are reasonably accurate, provided appropriate input data. Errors are introduced into results by the inherent uncertainty associated with the physics and formulation used to model dispersion, and by imprecise input parameters, such as emission and meteorological data [NIWAR, 2002].

5.3.3 Hazard identification

There is a distinction between a hazard and risk. A hazard is something that has the potential to cause damage to life, the environment and property. Risk is the probability that a hazard will manifest itself [Withers, 1988]. Once a hazard has been identified, it is necessary to evaluate the hazard in terms of the risk it presents [Harwood & Russell, 1989].

The traffic surveys and subsequent analysis in Chapter 3 may be regarded as the hazard identification process. A listing of the dangerous goods, belonging to Danger group I (substances that present a very severe risk), which are being transported through the Bayhead Road – South Coast Road; Edwin Swales VC Drive – South

Coast Road; Tara Road – Duranta Road; M4 Southern Freeway – Duranta Road; and The Avenue East – Refinery Drive intersections, was presented in Chapter 3. This listing is reproduced in Table 5.2.

Table 5.2: Dangerous goods allocated to Danger group I, transported through selected intersections

	Intersection				
Dangerous Goods	**Tara Road – Duranta Road**	**M4 Southern Freeway – Duranta Road**	**The Avenue East – Refinery Drive**	**Bayhead Road – South Coast Road**	**Edwin Swales VC Drive – South Coast Road**
Anhydrous Hydrogen Fluoride	√	√	√		
Acrylonitrile				√	√
Benzene	√	√	√	√	
Isopropylamine				√	√
Tetra Ethyl Lead	√		√	√	√
Methyl Isocyanate	√	√			

A summary of relevant characteristics of the dangerous goods listed in Table 5.2 follows.

- **Anhydrous Hydrogen Fluoride**

Anhydrous Hydrogen Fluoride is a colourless fuming liquid with a strong, irritating odour. Potential symptoms of exposure include: irritation of the eyes, skin, nose and throat; pulmonary oedema; eye and skin burns; bronchitis; and bone changes. Inhalation of mist or vapours may be fatal [NIOSH, 2002].

- **Acrylonitrile**

Acrylonitrile is a colourless to pale-yellow liquid with an unpleasant odour. Potential symptoms of exposure include: irritation of the eyes and skin; asphyxia; headache; sneezing; nausea, vomiting; lassitude (i.e. weakness, exhaustion); and dizziness. When heated or burned, toxic Hydrogen Cyanide gas is formed. Acrylonitrile is a potential carcinogen. Inhalation of vapours may result in collapse and possible death [NIOSH, 2002].

- **Benzene**

Benzene is a colourless to light-yellow liquid with an aromatic odour. Potential symptoms of exposure include: irritation of the eyes, skin, nose, respiratory system; dizziness; headache, nausea; anorexia, lassitude; dermatitis; and bone marrow depression. Benzene is a potential carcinogen. Inhalation of vapours may result in coma and possible death [NIOSH, 2002].

- **Isopropylamine**

Isopropylamine is a colourless liquid with an ammonia-like odour. Potential symptoms of exposure include: irritation of the eyes, skin, nose, throat; pulmonary oedema; visual disturbance; eye and skin burns; and dermatitis [NIOSH, 2002].

- **Tetra Ethyl Lead**

Tetra Ethyl Lead is a colourless liquid (unless dyed red, orange, or blue) with a pleasant, sweet odour. Potential symptoms of exposure include: eye irritation, insomnia, lassitude, anxiety; hypotension, hypothermia, pallor, nausea, anorexia, weight loss; confusion, hallucinations, psychosis, mania, convulsions, and coma. Inhalation of vapours may be fatal [NIOSH, 2002].

- **Methyl Isocyanate**

Methyl Isocyanate is a colourless liquid with a sharp, pungent odour. Potential symptoms of exposure include: irritation of the eyes, skin, nose and throat; respiratory sensitisation, cough, pulmonary secretions, chest pain, breathing difficulty; asthma; eye and skin damage. Inhalation of vapours may be fatal [NIOSH, 2002]. Methyl Isocyanate was the hazardous chemical involved in the 1984 Bhopal disaster in India [Withers, 1988].

5.3.4 Physical and consequence modelling

The adverse human consequences associated with a dangerous goods release may be quantified using a dose-response analysis. A dose-response analysis relates the intensity of the concentration and the exposure duration to the degree of injury. A large release of a toxic substance may result in irritation, non-lethal injury or death to persons. The impact assessment of toxic vapours involves a comparison of downwind concentrations estimated by the dispersion model with public exposure guidelines, including the Emergency Response Planning Guidelines (ERPG's) and the Immediately Dangerous to Life or Health concentration (IDLH) [Lines, 1995].

The ERPG's were developed by the American Industrial Hygiene Association. The *ERPG–3* is the maximum airborne concentration *below* which it is believed nearly all individuals could be exposed for up to one hour without experiencing or developing life-threatening health effects. The *ERPG–2* is the maximum airborne concentration *below* which it is believed nearly all individuals could be exposed for up to one hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action. The *ERPG–1* is the maximum airborne concentration *below* which it is believed nearly all individuals could be exposed for up to one hour without experiencing other than mild transient adverse health effects or perceiving a clearly defined objectionable odour. The values derived for the Emergency Response Planning Guidelines are not expected to protect everyone, but are applicable to most individuals in the general population. For emergency response applications, the ERPG's are widely considered to be the best health criteria available [Lines, 1995].

IDLH values were originally developed by the U.S. National Institute for Occupational Safety and Health (NIOSH) to ensure that a worker could escape from a given contaminated environment in the event of failure of the respiratory protection equipment. The current definition for an Immediately Dangerous to Life or Health Condition is a situation "that poses a threat of exposure to airborne contaminants when that exposure is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment" [NIOSH, 2002]. As a safety margin, the IDLH values were based on the effects that might occur as a consequence of a 30-minute exposure. Essentially, the IDLH value is the maximum concentration to which a healthy person may be exposed for thirty minutes without experiencing irreversible health effects along with severe eye or respiratory irritation and other effects (e.g., disorientation or incoordination) that could prevent escape [NIOSH, 2002]. Exposure guidelines for the dangerous goods belonging to Danger group I, which are being transported through the selected intersections, are presented in Table 5.3.

Table 5.3: Relevant exposure guidelines for selected chemicals [NIOSH, 2002]

Dangerous Goods	ERPG-1 [ppm]	ERPG-2 [ppm]	ERPG-3 [ppm]	IDLH [ppm]
Anhydrous Hydrogen Fluoride	2	20	50	30
Acrylonitrile	10	35	75	85
Benzene	50	150	1000	500
Isopropylamine	Not yet available			750
Tetra Ethyl Lead				3
Methyl Isocyanate	0.025	0.5	5	3

5.3.5 Emission rate modelling

Peak modelled ground-level concentrations are directly related to the emission rate, thus it is important:

- to use a rate which is sufficiently large to cover the worst case discharge of concern
- that the period that the maximum emission lasts for, matches the averaging period of the relevant exposure guideline [NIWAR, 2002].

In a traffic accident, the cargo tank on a dangerous goods vehicle could be crushed or punctured [Pet-Armacost et al. 1999]. Road tanker vehicles typically have several compartments [Infosource, 2001] and only a single compartment may be ruptured during an accident [Brown, Dunn & Policastro, 2001]. The fraction of the total capacity that is released is defined as the discharge fraction. A ruptured compartment will readily release its contents, leading to a discharge fraction close to one [Brown et al. 2001]. The total release amount and the release rate of material from the container are dependent on the size and location of the hole in the container, which in turn depend on the nature and severity of the accident [Harwood & Russell, 1989].

The dangerous goods listed in Table 3.7, which are being transported through the chosen intersections, are all liquids or fuming liquids at ambient temperatures [NIOSH, 2002]. Liquids released from the container that are not flashed or entrained with the flashed liquid, form a pool on the ground, which expands and contracts in response to gravity-driven fluid flow and evaporation. Equilibrium pool depth varies based on the volume of material released, i.e. the average pool depth for larger releases is greater than that for small releases [Kawamura & Mackay, 1985]. Pool evaporation may be estimated using a time-dependent, energy-budget model that considers heat transfer to and from the pool via radiation, convection, conduction, and evaporation. The energy budget of an evaporating pool is a balance between solar radiation, incoming longwave radiation, outgoing longwave radiation, convective heat transfer and conductive heat transfer to the ground [Brown et al. 2001]. Evaporation rate is also dependent on the wind speed, the molecular weight of the selected chemical, and the vapour pressure of the selected chemical [Kawamura & Mackay, 1985].

Thus, the emission rate value entered into the dispersion model depends on the release rate of material from the damaged tanker and the rate of evaporation from the subsequent liquid pool.

5.3.6 Surface roughness

Friction between the ground and air passing over it is one cause of mechanical turbulence. The nature of the ground surface may influence dispersion by affecting the amount of atmospheric turbulence. To account for the nature of the surrounding land use, a surface roughness length of one metre has been specified, in line with ADMS™ recommendations for cities [CERC, 2001]. When all else is equal, a hazard area will be *smaller* when a *larger* surface roughness value is chosen because greater turbulence develops as surface roughness increases [US-EPA, 1999b].

5.3.7 Effect of study area topography on dispersion

The dispersion of atmospheric contaminants from a dangerous goods release may be greatly affected by the nature of the surrounding terrain. Topographical features may increase or decrease the estimated ground level concentrations, or change the plume trajectory without changing the maximum ground level concentrations [US-EPA, 1998]. ADMS™ contains algorithms to model complex terrain. The method used by ADMS™ to incorporate the effects of terrain is relatively sophisticated; the actual wind flow patterns are predicted, then the plume is dispersed within this modified flow stream. Surrounding topographical features are integrated into a terrain file, which contains grid co-ordinates and heights. This terrain file is used in ADMS™ to estimate the effect of the terrain on plume dispersion. In ADMS™, the complex terrain module cannot be run in conjunction with the coastline and puff release modules [CERC, 2001].

The Durban South Basin consists of a fairly flat coastal plain surrounded by a steep ridgeline to the south and a ridge of hills, approximately 100–150 metres high, to the west. To the north, the coastal plain widens around the harbour before narrowing again towards the Umgeni River [CSIR, 1999]. The coastal edge of the Durban South Basin consists of a major dune that ultimately forms the Bluff at the harbour mouth. The top of this dune is approximately eighty metres above sea level and seventy-five metres above the floor of the Durban South Basin. Except at river mouths, the Bluff virtually cuts the main region of coastal plain off from the ocean [CSIR, 1999]. This unique topography of the Durban South Basin (illustrated in Figure 5.10) plays a significant role in controlling local wind flows and affects the dispersion of pollutants [Preston-Whyte & Tyson, 1988]. Consequently, the treatment of terrain has been identified as a key element in this investigation.

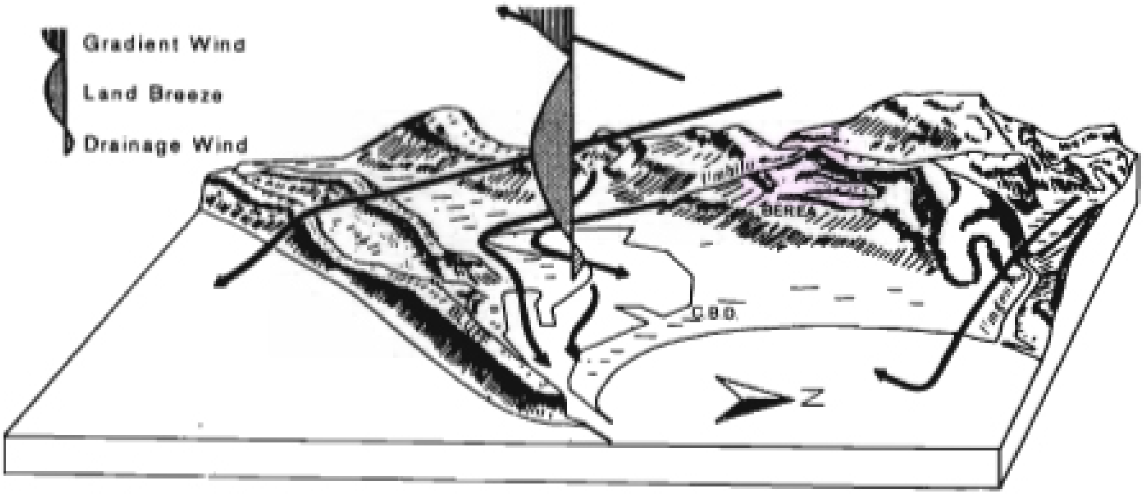


Figure 5.10: The topography of Durban South Basin [Preston-Whyte & Tyson, 1988]

The ADMS™ terrain files used in this assessment have been created from data provided by eThekwini Municipality Water Services and the eThekwini Municipality GIS Department. Separate terrain grids were created for the area surrounding each of the five surveyed intersections, extending 10.5 kilometres in the north–south and east–west directions with an average spacing of approximately 150 metres.

Dispersion modelling was undertaken at the Bayhead Road – South Coast Road, Edwin Swales VC Drive – South Coast Road, Tara Road – Duranta Road, M4 Southern Freeway – Duranta Road, and The Avenue East – Refinery Drive intersections, in order to assess the site-specific effect of interactions between terrain, wind speed and wind direction on a dispersing plume.

Meteorological data from the weather station at the Durban International Airport, which is within the Durban South Basin, was utilised in this investigation. The South African

Weather Service provided hourly average wind speed, wind direction, air temperature, relative humidity and global radiation data for the years 1993-2002. An accurate estimate of the depth of the mixing layer is essential if dispersion of contaminants released in the boundary layer is to be modelled correctly. The South African Weather Service does not record boundary layer height. If the user does not specify boundary layer depth in ADMS™, the dispersion model's estimate of boundary layer depth for a particular hour is improved if meteorological data for all the preceding hours from midnight are provided [CERC, 2001].

The dispersion modelling simulations were conducted using every hour of meteorological conditions for the four-year period (1999–2002). A four-year period was utilised, as ADMS™ has a limit to the number of lines of meteorological data that may be used in a single run [CERC, 2001]]. A comparison of the wind roses for the two sets of meteorological data presented in Figure 5.11, illustrates that the meteorological data for the years 1999–2002 are representative of the meteorological conditions for the ten-year period 1993–2002. The years 1999–2002 show a slight increase in the percentage of calms.

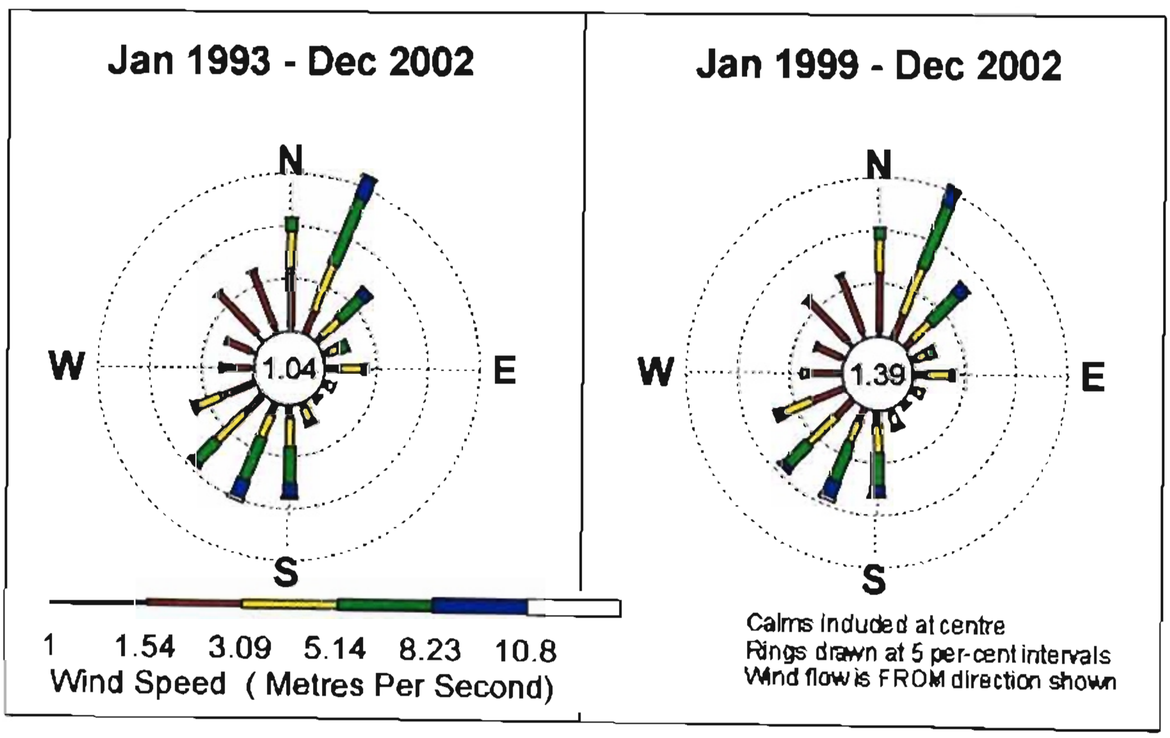


Figure 5.11: A comparison of the annual average wind roses for the Durban International Airport, 1993–2002 and 1999–2002

The dispersion of a neutrally buoyant (*passive*) gas was simulated at each of the five intersections using a continuous unit emission rate of 1 kg/s. A passive release has the same density has the ambient air. As the dispersion modelling simulations were conducted using every hour of meteorological conditions for a four-year period (1999–2002), all wind directions and atmospheric stabilities would have been encapsulated. The maximum (i.e. 100th percentile) concentration contours for identical release conditions and meteorological data at each intersection, have been plotted onto scaled maps in Figure 5.12. These plotted concentration contours (isopleths) represent the highest ground-level concentration that could be expected at each point within the study area, resulting from a 1 kg/s passive gas release under all feasible meteorological conditions. The output concentrations are given in units of $\mu g/m^3$ (micrograms of vapour or gas per cubic meter of contaminated air). A concentration averaging time of one hour was specified in ADMS^{TM}. Averaging times are used by the dispersion model to estimate the component of lateral (across-wind) plume spread due to variations in the mean wind direction [US-EPA, 1998].

Figure 5.12 illustrates that the surrounding terrain is a key factor associated with dangerous goods releases in the Durban South Basin. When compared with the dispersion modelling results for flat terrain (Figure 5.12a), it is evident that topographical features in the basin (Figure 5.12b–f) have the effect of reducing the size of the hazard area or *footprint*. Clearly, the ridge of hills to the west, the ridgeline to the south and the dune on the eastern (coastal) edge of the Durban South Basin act to constrain the plumes in those directions. Terrain channelling of the plumes is also evident, especially in Figure 5.12(d): the plumes are channelled through the narrowing of two hills to the northeast of the intersection. Figure 5.12(c) and (d) also illustrate that the plumes travel towards the lower ground at the harbour. The terrain plots in Figure 5.12(b–f) may be interpreted as the plumes moving along the path of least resistance, following the line of least change in terrain.

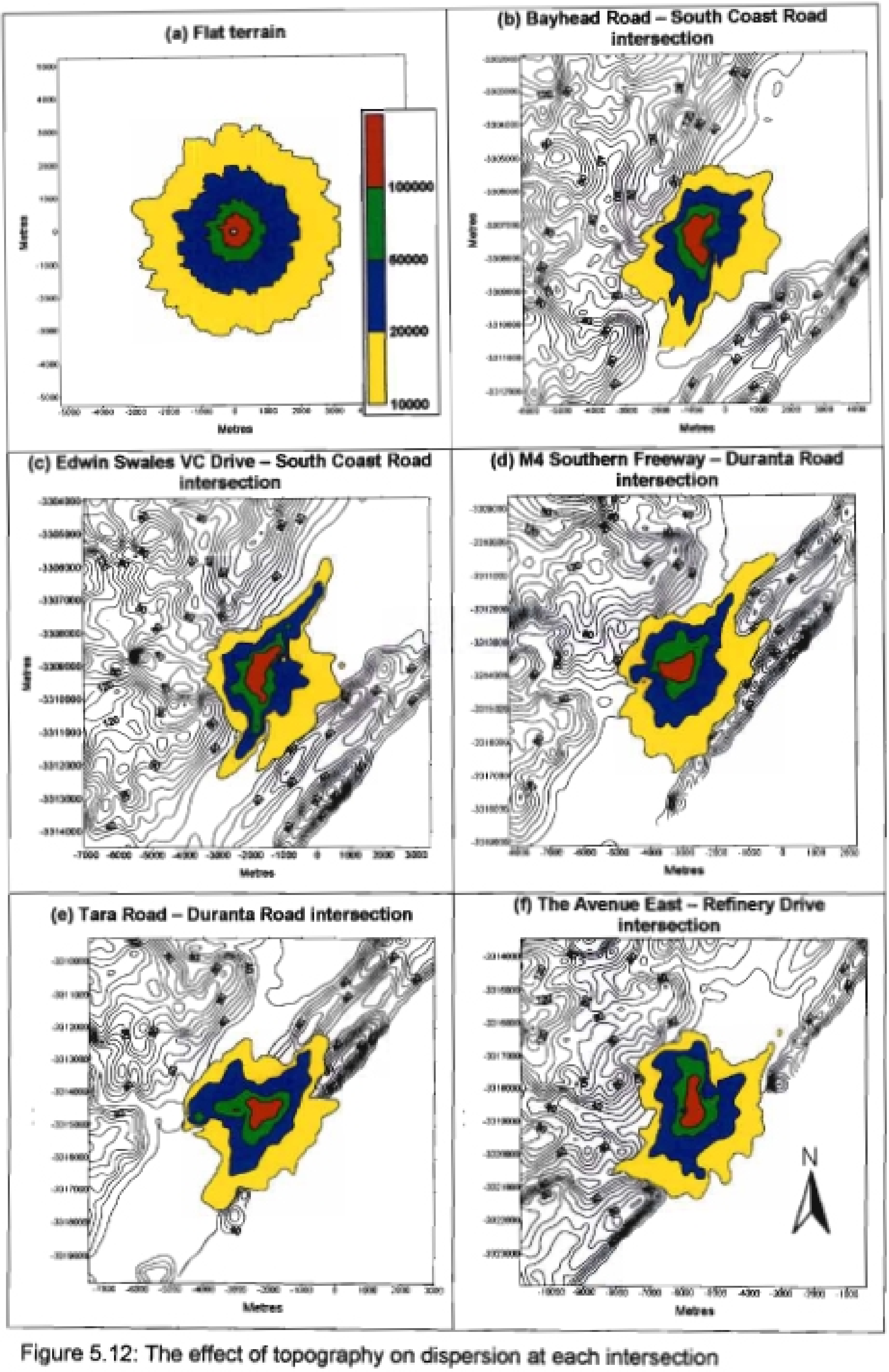


Figure 5.12: The effect of topography on dispersion at each intersection

Figure 5.12 confirms that complex and diverse interactions arise between wind speed, wind direction and local terrain. Topographical features (e.g. hills, ridges, valleys, escarpments and slopes) may deflect plumes considerably to almost 90° from the original wind direction. While terrain and wind direction may affect the direction of the plume, a relationship also exists between terrain and wind speed. Topographical features have an influence on the wind speed as it passes over them [McKendry, Looney & McKenzie, 2002].

Figure 5.13(a) illustrates that as air approaches a shallow slope (slope angle $\alpha<17^{o}$), wind speed reduces to a minimum value at the base of the slope, then increases to a maximum value near the crest of the slope, and thereafter decelerates to a constant value downwind. As the slope angle increases above 17°, up-slope flow produces separation of the airflow at the base of the slope and at the crest, resulting in reverse flow at both of these locations (Figure 5.13b). Flow down the slope creates reverse flow only at the base and not at the crest (Figure 5.13c). Wind speed also increases through valleys. These changes in airflow around topographical features undoubtedly influence turbulence and the mixing of contaminants [McKendry et al. 2002].

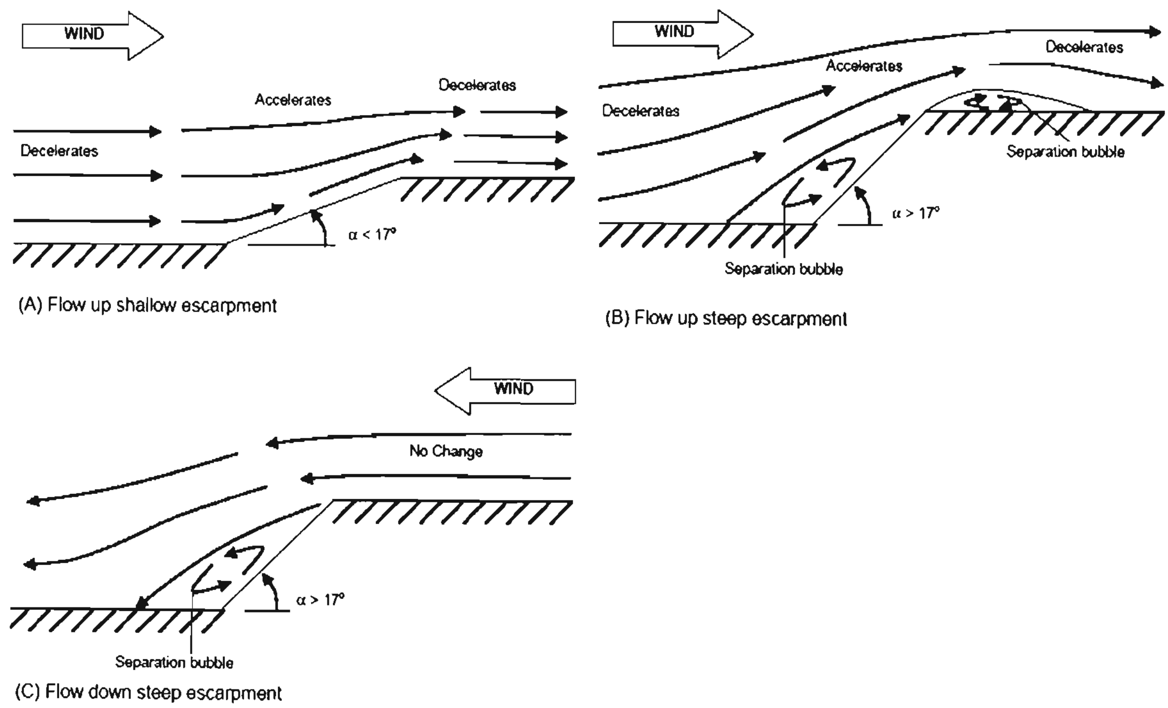


Figure 5.13: Wind flow over escarpment [after McKendry et al. 2002]

5.4 Risk Assessment Methodology

This section outlines the methodology that has been utilised to assess the significance and extent of the impact in the event of a dangerous goods release. The aim of investigating toxic vapour clouds resulting from a dangerous goods release is to identify areas that may be exposed or affected, or individuals who may be subject to injury or death.

5.4.1 Concentration conversion factors

The dispersion model ADMS^{TM} calculates the downwind concentrations in units of $\mu g/m^3$. Each chemical has a unique numerical factor for the conversion of concentrations in units of $\mu g/m^3$ to ppb (parts of vapour or gas per billion parts of contaminated air by volume). This conversion factor is a function of the molecular weight of the chemical [NIOSH, 2002]. Conversion factors for the dangerous goods belonging to Danger group I, which are being transported through the selected intersections, are presented in Table 5.4.

Table 5.4: Conversion factors for selected chemicals [NIOSH, 2002]

Dangerous Goods	Conversion Factor ($\mu g/m^3$ to ppb)
Anhydrous Hydrogen Fluoride	1.220
Acrylonitrile	0.461
Benzene	0.313
Isopropylamine	0.413
Tetra Ethyl Lead	0.075
Methyl Isocyanate	0.427

5.4.2 Implications of using a deterministic dispersion modelling approach

The parameters that affect the consequences of a dangerous goods spill, e.g. release quantity, surrounding population density and meteorology (comprising wind speed, wind direction, temperature, cloud cover, relative humidity, global radiation, etc) vary temporally at a given location. Thus, these parameters, like accident probability and release probability discussed in Chapter 4, are actually continuous distributions. Accordingly, the consequences also follow a distribution. Deterministic techniques that attempt to fix the various input parameters to mean values and obtain an average consequence value are essentially flawed because they ignore the true range of the possible consequences. Such approaches may lead to erroneous conclusions [Brown et al. 2001].

5.4.3 Treatment of specific chemicals

As ADMS^{TM} does not support probabilistic sampling of input variables, a surrogate measure was employed. As discussed in Section 5.3.7, dispersion modelling simulations were conducted at each of the five intersections for a passive gas, using a continuous emission rate of 1 kg/s. These simulations were conducted using every hour of meteorological conditions for a four-year period (1999–2002). Hence, all wind directions and atmospheric stabilities have been encapsulated. The concentration averaging time of one hour, specified in ADMS^{TM} is still appropriate, as the ERPG's are based on a one-hour exposure [Lines, 1995].

In order to estimate downwind concentrations resulting from the release of a specific chemical (for a 1 kg/s emission rate), the numerical ADMS^{TM} output at each intersection from Section 5.3.7, must be scaled by the appropriate factor for the conversion of concentrations in units of $\mu g/m^3$ to ppb (presented in Table 5.4). Exposure limits for chemicals are usually expressed in units of ppm (parts of vapour or gas per million parts of contaminated air by volume). Hence, the concentrations in units of ppb must be scaled into units of ppm, to enable comparison to the relevant exposure limits.

As discussed in Section 5.3.5, that the dangerous goods emission rate into the atmosphere depends on the release rate of material from the damaged container and the rate of evaporation from the subsequent liquid pool. The dangerous goods belonging to Danger group I, which are being transported through the selected intersections (listed in Table 3.7), are carried in mild steel ISO-tainers [Ecoserv, 2003; de Klerk, 2004] or in road tankers. The number of compartments within a road tanker and the capacity of each compartment vary according to the tanker configuration. Up to six kilolitres of dangerous goods may be carried in each compartment [Perry, 2003]. Specifying a 1 kg/s continuous emission rate in ADMS^{TM} means that a total quantity of 3.6 metric tons of dangerous goods is released into the atmosphere over the course of one hour. Table 5.5 reveals that if just a single six-kilolitre compartment is ruptured during an accident, the quantity of material released will exceed 3.6 metric tons.

Table 5.5: Mass of dangerous goods released in the event of a rupture to a six-kilolitre compartment in a tanker

Dangerous Goods	Liquid Density [kg/m^3] [NIOSH, 2002]	Release Mass [Metric tons]
Anhydrous Hydrogen Fluoride	972	5.8
Acrylonitrile	806	4.8
Benzene	885	5.3
Isopropylamine	688	4.1
Tetra Ethyl Lead	1653	9.9
Methyl Isocyanate	958	5.8

5.4.4 Treatment of specific release scenarios

Experimentation and CERC [2001] have revealed that downwind concentrations estimated by ADMS™ are directly proportional to the emission rate. In order to estimate the downwind concentrations resulting from different release scenarios, i.e. emission rates other than 1 kg/s, the ADMS™ output for specific chemicals at each intersection should be scaled by the new emission rate.

5.4.5 Application of geographical information systems (GIS)

Through the use of geographical information systems (GIS), plume coordinates, information about the population distribution, transportation network, and spatial and environmental data have been integrated. Dispersion modelling is thus enhanced as consequences and population exposure may be estimated more efficiently. GIS data used in this investigation was provided by eThekwini Municipality Water Services and the eThekwini Municipality GIS department. Actual consequence measures associated with the release of dangerous goods are difficult to predict accurately and are often represented by population density figures. The use of population density figures assumes that the actual consequences are proportional to the population exposed to a release [FHWA, 1994].

5.5 Risk Assessment Results

Employing the methodology outlined in Section 5.4, the impact of releases of selected dangerous goods at each of the five intersections is estimated in this section.

5.5.1 Bayhead Road - South Coast Road intersection

- **Large Acrylonitrile release**

Figure 5.14 presents isopleths indicating the downwind distances to the exposure limits: ERPG-1, ERPG-2, ERPG-3 and IDLH, respectively for an Acrylonitrile release (1 kg/s emission rate) at the Bayhead Road – South Coast Road intersection. These 100th percentile isopleths (and other isopleths plotted throughout Section 5.5) do not represent the concentrations during a single incident. Rather, they reflect the highest concentration value that could be expected at any point within the study area, resulting from a 1 kg/s Acrylonitrile release under all feasible meteorological conditions.

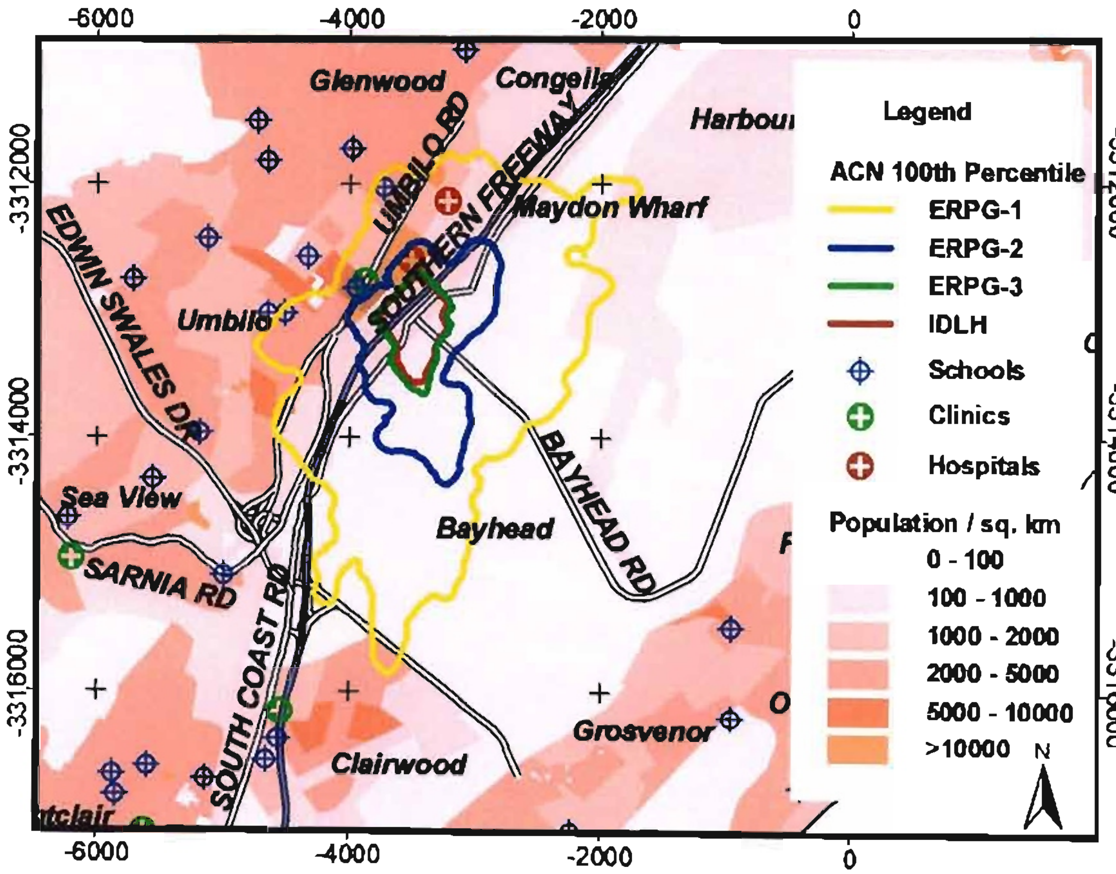


Figure 5.14: The extent of the impact on the area surrounding the Bayhead Road – South Coast Road intersection of ground level concentrations following an Acrylonitrile (ACN) release (1 kg/s emission rate), using the ERPG and IDLH guidelines

The ERPG-2 isopleth is generally accepted as the limit of emergency response [Brown et al. 2001]. Figure 5.14 indicates that concentrations of Acrylonitrile above the ERPG-2 level may exist as far out as 1.3 kilometres from the intersection. The ERPG-2 isopleth in Figure 5.14 covers an area of 1.3 square kilometres. The residential population density is relatively low in the industrial areas to the east of the Bayhead Road – South Coast Road intersection. Approximately 1700 residents within the ERPG-2 isopleth are potentially at risk, and if exposed would be expected to experience irreversible or other serious health effects that could impair their ability to take protective actions. Using GIS, the number of people at risk was estimated as the product of the size of the ERPG-2 impact area and the population density within the impact area.

Depending on the direction the wind is blowing towards, in the event of a large Acrylonitrile release, it is recommended that King Edward VIII hospital, the affected parts of the residential area of Umbilo; and the affected parts of the Maydon Wharf and Bayhead industrial areas within the ERPG-2 isopleth, be notified or possibly evacuated until the spill has been contained and removed. The King Edward VIII hospital is a vulnerable zone where a large number of people who are difficult to protect or evacuate, are concentrated. Occupants of vehicles travelling on roads close to the Bayhead Road – South Coast Road intersection (e.g. M4 Southern Freeway, Umbilo Road) may be exposed to high concentrations of Acrylonitrile for short periods of time as they travel through and along the dispersing plume, especially near the source. Section 5.6 outlines the methodology that may be employed to investigate the health impact to road users, who are caught in queues that have formed on Bayhead Road and South Coast Road as a result of an accident causing this release.

- **Worst-case Acrylonitrile release**

The U.S. Environmental Protection Agency and the National Oceanic and Atmospheric Administration developed the dispersion model ALOHA (Areal Locations of Hazardous Atmospheres) to assist emergency response personnel. Unlike ADMS™, ALOHA is able to model evaporation from a pool on the ground. ALOHA accounts for the effect on pool temperature of several kinds of heat energy exchange between the pool and its environment to estimate pool evaporation rate [US-EPA, 1999b]. During the traffic surveys described in Chapter 3, Acrylonitrile was identified as being transported in ISO-tainers. ISO-tainers have no internal compartments and the capacity of an ISO-tainer may be up to twenty-five kilolitres [Perry, 2003].

Consider the following release scenario:

- twenty kilolitres of Acrylonitrile are released from an ISO-tainer and form an unconfined pool on the ground
- a typical wind speed of 4 m/s and ambient temperature of 25°C prevail, corresponding to neutral conditions (Pasquill stability class C)

ALOHA estimates that approximately 11.9 metric tons of Acrylonitrile will be released into the atmosphere over a one-hour period. This equates to a continuous emission rate of 3.3 kg/s. ALOHA's estimate is comparable to the emission rate estimated using the method of Kawamura & Mackay [1985] detailed in Appendix D.

Figure 5.15 presents isopleths indicating the downwind distances to the exposure limits: ERPG-2, ERPG-3 and IDLH, respectively for an Acrylonitrile release (3.3 kg/s emission rate) at the Bayhead Road – South Coast Road intersection.

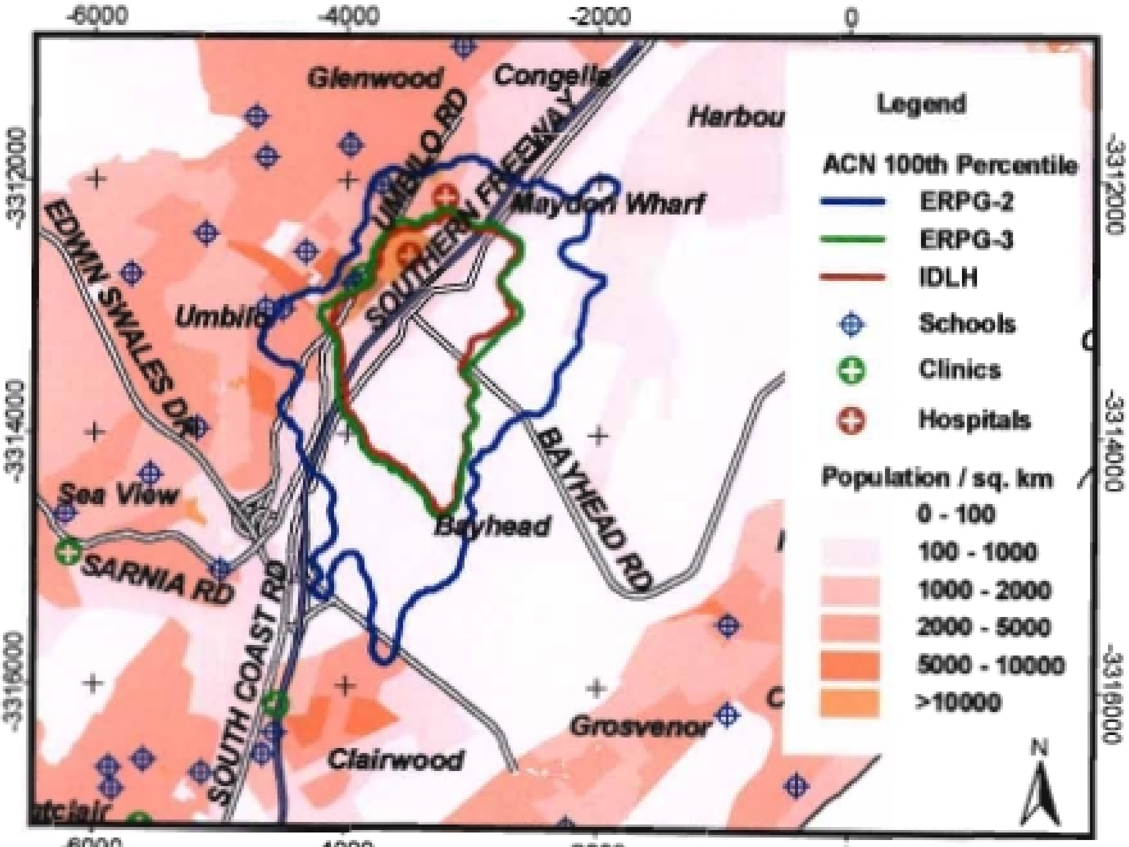


Figure 5.15: The extent of the impact on the area surrounding the Bayhead Road – South Coast Road intersection of ground level concentrations following an Acrylonitrile (ACN) release (3.3 kg/s emission rate), using the ERPG and IDLH guidelines

Figure 5.15 indicates that concentrations of Acrylonitrile above the ERPG-2 level may exist as far out as 2.7 kilometres from the intersection. The ERPG-2 isopleth in Figure 5.15 covers an area of 5.4 square kilometres. Approximately 5700 residents within the ERPG-2 isopleth are potentially at risk, and if exposed would be expected to experience irreversible or other serious health effects that could impair their ability to take protective actions. Depending on the direction the wind is blowing towards, in the event of such a worst-case Acrylonitrile release, it is recommended that the affected schools and hospitals, including the King Edward VIII hospital; the affected parts of the residential areas of Clairwood, Umbilo and Glenwood; and the affected parts of the Maydon Wharf, Bayhead and Congella industrial areas within the ERPG-2 isopleth, be notified or possibly evacuated until the spill has been contained and removed. Occupants of vehicles travelling on the M4 Southern Freeway, Umbilo Road, Sarnia Road and Edwin Swales VC Drive may be exposed to high concentrations of Acrylonitrile for short periods of time as they travel through and along the dispersing plume, especially near the source.

5.5.2 Edwin Swales VC Drive – South Coast Road intersection

- **Large Acrylonitrile release**

Figure 5.16 presents isopleths indicating the downwind distances to the exposure limits: ERPG-1, ERPG-2, ERPG-3 and IDLH, respectively for an Acrylonitrile release (1 kg/s emission rate) at the Edwin Swales VC Drive – South Coast Road intersection.

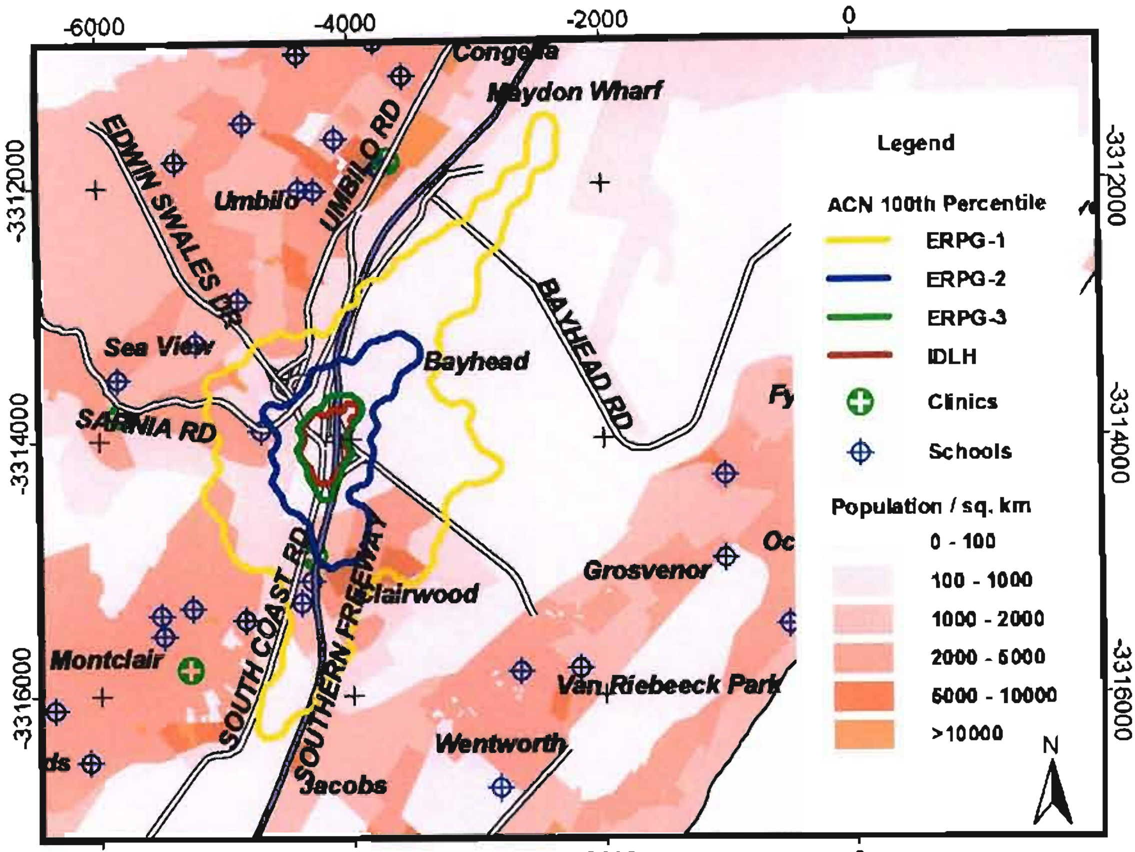


Figure 5.16: The extent of the impact on the area surrounding the Edwin Swales VC Drive – South Coast Road intersection of ground level concentrations following an Acrylonitrile (ACN) release (1 kg/s emission rate), using the ERPG and IDLH guidelines

Figure 5.16 indicates that concentrations of Acrylonitrile above the ERPG-2 level may exist as far out as 1.1 kilometres from the intersection. The ERPG-2 isopleth in Figure 5.16 covers an area of 1.3 square kilometres. The residential population density is relatively low in the industrial areas immediately surrounding the Edwin Swales VC Drive – South Coast Road intersection. Approximately five hundred residents within the ERPG-2 isopleth are potentially at risk, and if exposed would be expected to experience irreversible or other serious health effects that could impair their ability to take protective actions. Depending on the direction the wind is blowing towards, in the event of a large Acrylonitrile release, it is recommended that the affected parts of the Clairwood and Sea View residential areas; and the affected parts of the Maydon Wharf and Bayhead industrial areas within the ERPG-2 isopleth, be notified or possibly evacuated until the spill has been contained and removed. Occupants of vehicles travelling on roads close to the Edwin Swales VC Drive – South Coast Road intersection (e.g. M4 Southern Freeway, Sarnia Road) may be exposed to high concentrations of Acrylonitrile for short periods of time as they travel through and along the dispersing plume, especially near the source. Section 5.6 outlines the methodology that may be employed to investigate the health impact to road users, who are caught in queues that have formed on Edwin Swales VC Drive and South Coast Road as a result of an accident causing this release.

- **Worst-case Acrylonitrile release**

Figure 5.17 presents isopleths indicating the downwind distances to the exposure limits: ERPG-2, ERPG-3 and IDLH, respectively for an Acrylonitrile release (3.3 kg/s emission rate) at the Edwin Swales VC Drive – South Coast Road intersection.

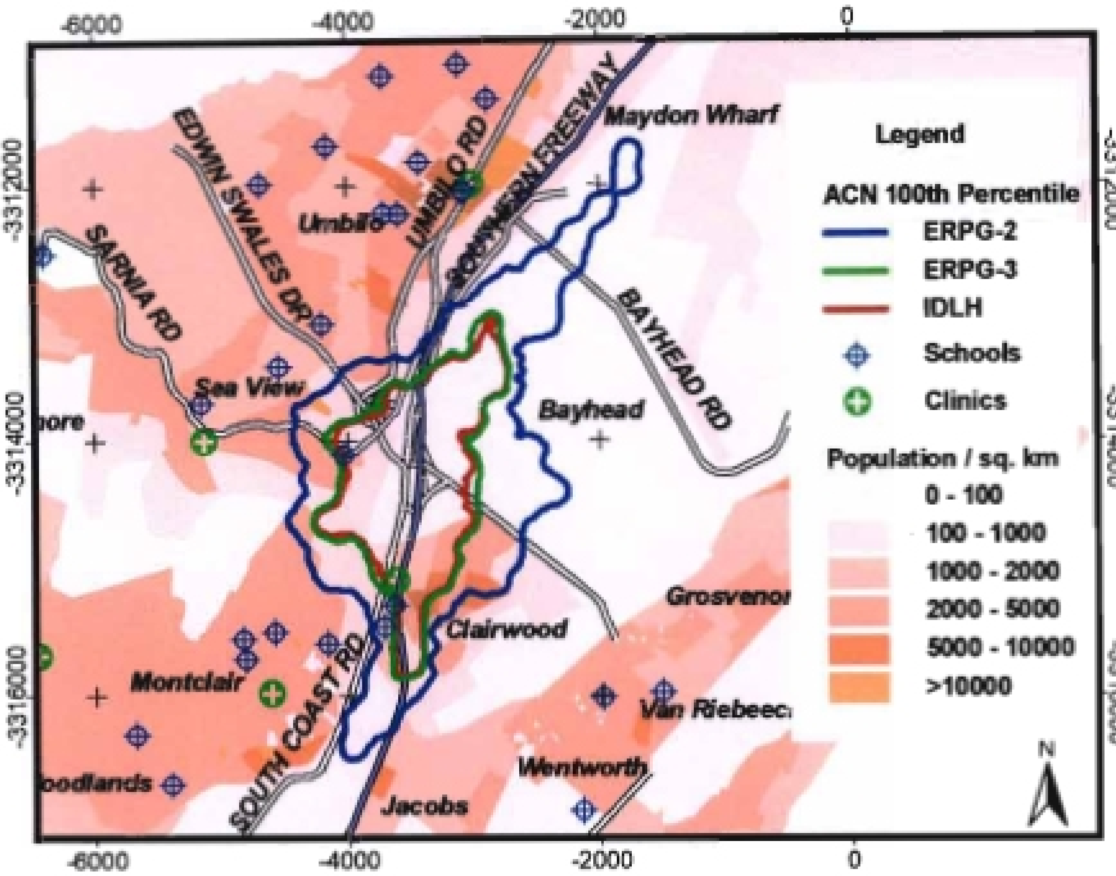


Figure 5.17: The extent of the impact on the area surrounding the Edwin Swales VC Drive – South Coast Road intersection of ground level concentrations following an Acrylonitrile (ACN) release (3.3 kg/s emission rate), using the ERPG and IDLH guidelines

Figure 5.17 indicates that concentrations of Acrylonitrile above the ERPG-2 level may exist as far out as 3.3 kilometres from the intersection. The ERPG-2 isopleth in Figure 5.17 covers an area of 5.3 square kilometres. Approximately 5100 residents within the

ERPG-2 isopleth are potentially at risk, and if exposed would be expected to experience irreversible or other serious health effects that could impair their ability to take protective actions. Depending on the direction the wind is blowing towards, in the event of such a worst-case Acrylonitrile release, it is recommended that the affected parts of the Clairwood, Sea View and Montclair residential areas; the affected parts of the Maydon Wharf, Bayhead and Jacobs industrial areas; and the affected schools and clinics within the ERPG-2 isopleth, be notified or possibly evacuated until the spill has been contained and removed. Occupants of vehicles travelling on the M4 Southern Freeway, Sarnia Road and Umbilo Road may be exposed to high concentrations of Acrylonitrile for short periods of time as they travel through and along the dispersing plume, especially near the source.

5.5.3 M4 Southern Freeway – Duranta Road intersection

- **Large Anhydrous Hydrogen Fluoride release**

A monthly shipment of six metric tons of Anhydrous Hydrogen Fluoride is transported to the Engen Oil Refinery through the M4 Southern Freeway – Duranta Road intersection [de Klerk, 2004]. Specifying a 1 kg/s continuous emission rate in ADMS™ means that a total quantity of 3.6 metric tons is released into the atmosphere over the course of one hour. Figure 5.18 presents isopleths indicating the downwind distances to the exposure limits: ERPG-2, IDLH and ERPG-3, respectively for an Anhydrous Hydrogen Fluoride release (1 kg/s emission rate) at the M4 Southern Freeway – Duranta Road intersection.

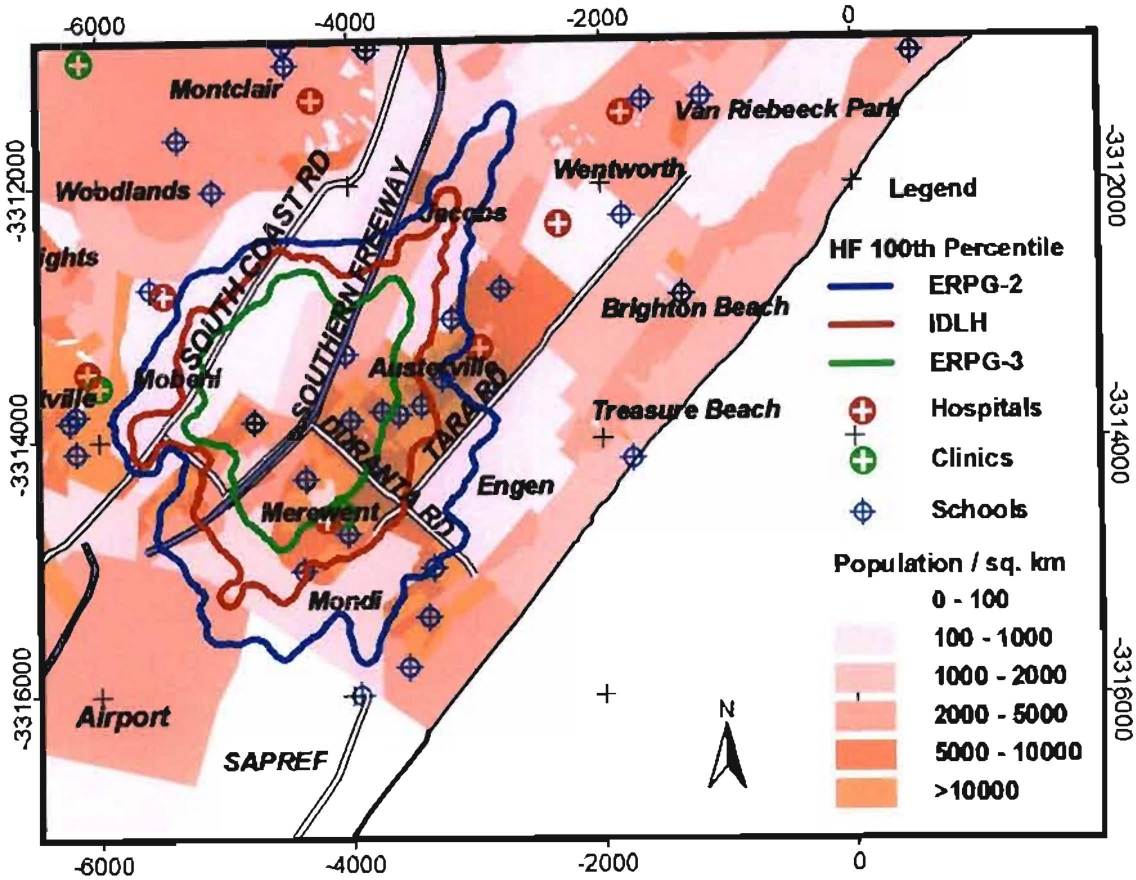


Figure 5.18: The extent of the impact on the area surrounding the M4 Southern Freeway – Duranta Road intersection of ground level concentrations following an Anhydrous Hydrogen Fluoride (HF) release (1 kg/s emission rate), using the ERPG and IDLH guidelines

Figure 5.18 indicates that concentrations of Anhydrous Hydrogen Fluoride above the ERPG-2 level may exist as far out as 3.1 kilometres from the intersection. The ERPG-2 isopleth in Figure 5.18 covers an area of 8.5 square kilometres. The residential population density is relatively high in the areas to the south and east of the M4 Southern Freeway – Duranta Road intersection. Approximately 35000 residents within the ERPG-2 isopleth are potentially at risk, and if exposed would be expected to experience irreversible or other serious health effects that could impair their ability to take protective actions. Depending on the direction the wind is blowing towards, in the event of a large Anhydrous Hydrogen Fluoride release at the M4 Southern Freeway – Duranta Road intersection, it is recommended that the affected parts of the residential areas of Clairwood, Austerville and Merewent; the affected parts of the Jacobs and Mobeni industrial areas, Mondi Paper, the Engen and SAPREF oil refineries; and the affected schools, hospitals and clinics within the ERPG-2 isopleth, be notified or possibly evacuated until the spill has been contained and removed. Occupants of vehicles travelling on roads close to the M4 Southern Freeway – Duranta Road intersection (e.g. along South Coast Road, Tara Road) may be exposed to high concentrations of Anhydrous Hydrogen Fluoride for short periods of time as they travel through and along the dispersing plume. Section 5.6 outlines the methodology that may be employed to investigate the health impact to road users, who are caught in queues that have formed on Duranta Road and the M4 Southern Freeway off-ramps as a result of an accident causing this release.

5.5.4 Tara Road – Duranta Road intersection

- **Large Anhydrous Hydrogen Fluoride release**

The monthly shipment of six metric tons of Anhydrous Hydrogen Fluoride to the Engen Oil Refinery is also transported through the Tara Road – Duranta Road intersection [de Klerk, 2004]. Figure 5.19 presents isopleths indicating the downwind distances to the exposure limits: ERPG-2, IDLH and ERPG-3, respectively for an Anhydrous Hydrogen Fluoride release (1 kg/s emission rate) at the Tara Road – Duranta Road intersection.

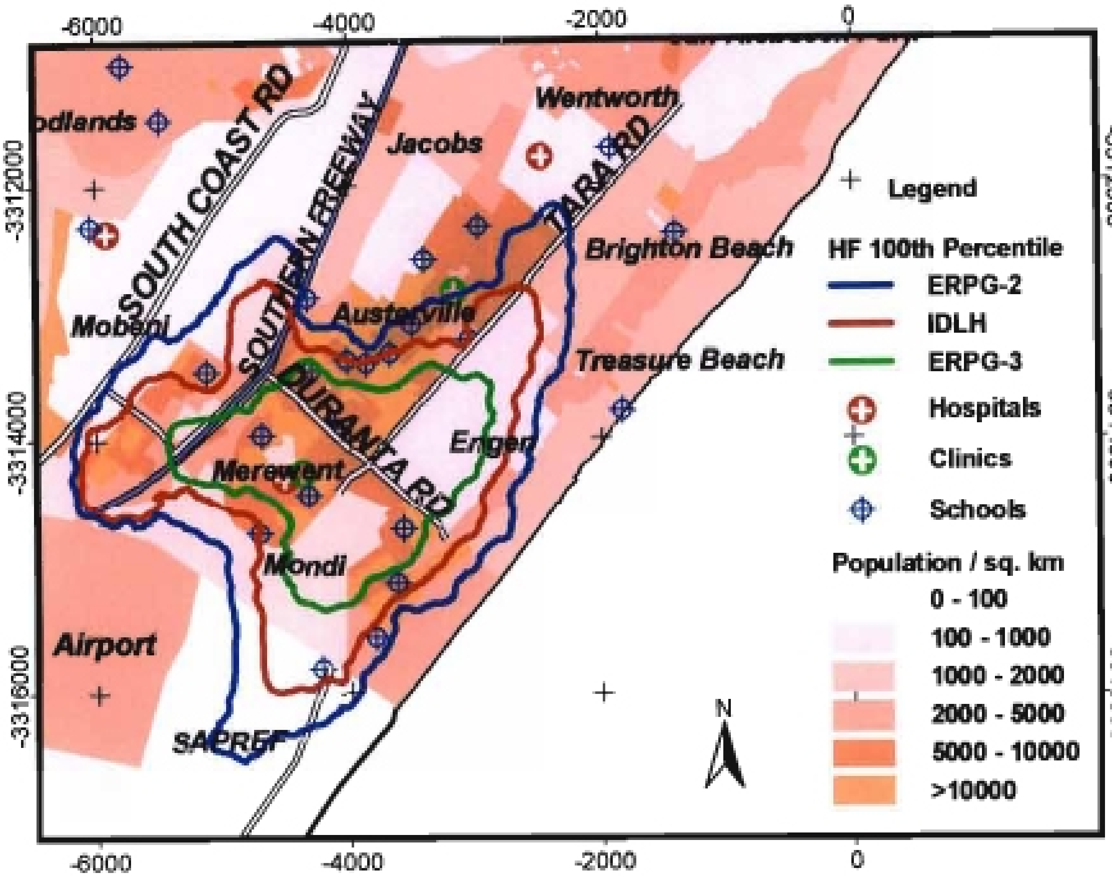


Figure 5.19: The extent of the impact on the area surrounding the Tara Road – Duranta Road intersection of ground level concentrations following an Anhydrous Hydrogen Fluoride (HF) release (1 kg/s emission rate), using the ERPG and IDLH guidelines

Figure 5.19 indicates that concentrations of Anhydrous Hydrogen Fluoride above the ERPG-2 level may exist as far out as 2.5 kilometres from the intersection. The ERPG-2 isopleth in Figure 5.19 covers an area of 8.4 square kilometres. The residential population density is relatively high in the areas surrounding the Tara Road – Duranta Road intersection. Approximately 37400 residents within the ERPG-2 isopleth are potentially at risk, and if exposed would be expected to experience irreversible or other serious health effects that could impair their ability to take protective actions. Depending on the direction the wind is blowing towards, in the event of a large Anhydrous Hydrogen Fluoride release at the Tara Road – Duranta Road intersection, it is recommended that the affected parts of the residential areas of Austerville, Merewent and Treasure Beach; the affected parts of the Mobeni industrial area, Mondi Paper, the Engen and SAPREF oil refineries; and the affected schools, hospitals and clinics within the ERPG-2 isopleth, be notified or possibly evacuated until the spill has been contained and removed. Occupants of vehicles travelling along the M4 Southern Freeway may be exposed to high concentrations of Anhydrous Hydrogen Fluoride for short periods of time as they travel through and along the dispersing plume. Section 5.6 outlines the methodology that may be employed to investigate the health impact to road users, who are caught in queues that have formed on Tara Road and Duranta Road as a result of an accident causing this release.

The 99.9th percentile ground-level concentration is the highest ground-level concentration at each grid point after the highest 0.1 per-cent of predictions has been discarded. Figure 5.20 provides an indication of the degree to which the chosen 100th percentile concentrations are representative, by presenting the 99.9th percentile ground-level concentrations. Figure 5.20 presents isopleths indicating the downwind distances to the ERPG-2 exposure limit for an Anhydrous Hydrogen Fluoride release (1 kg/s emission rate) at the Tara Road – Duranta Road intersection.

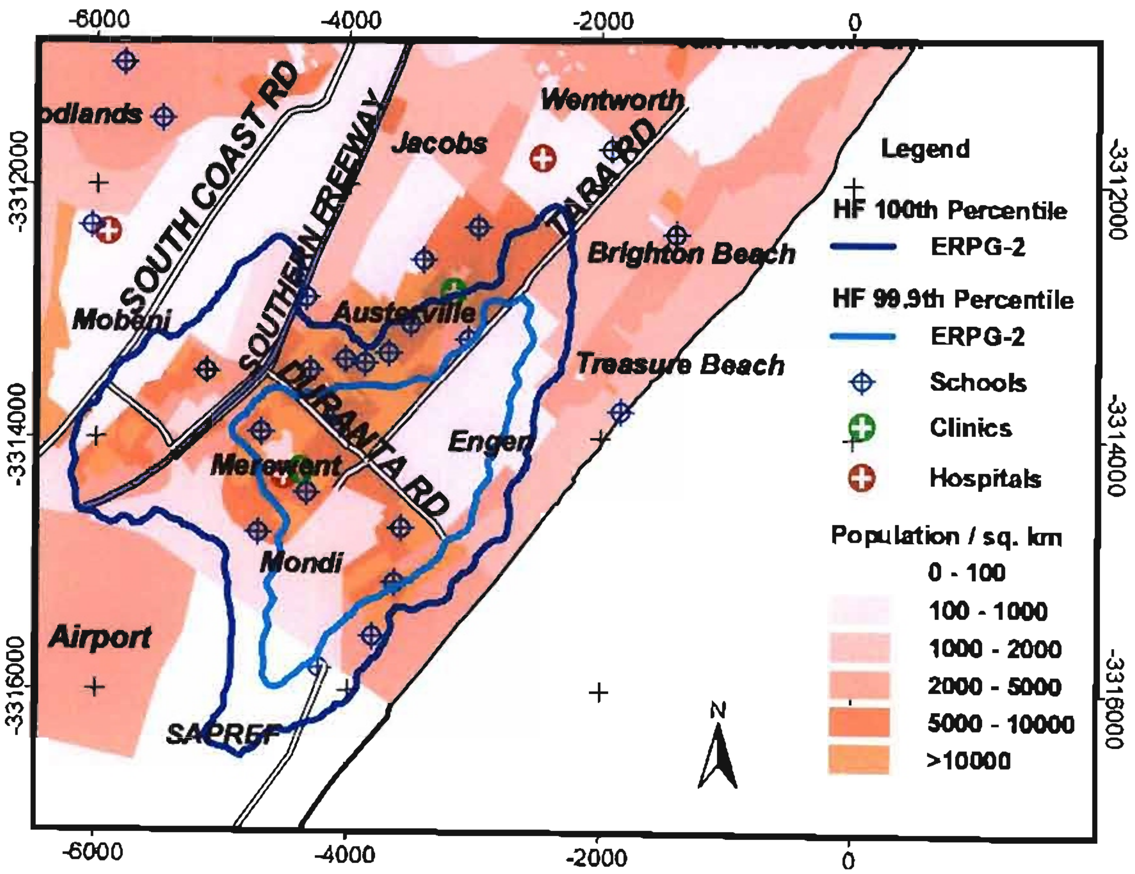


Figure 5.20: The extent of the impact on the area surrounding the Tara Road – Duranta Road intersection of ground level concentrations following an Anhydrous Hydrogen Fluoride (HF) release (1 kg/s emission rate), using the ERPG-2 guideline

The effects of topographical features are clearly evident in Figure 5.20. The dune on the eastern edge of the Durban South Basin acts to constrain the plumes in that direction and the 99.9th percentile ERPG-2 isopleth is slightly within the 100th percentile ERPG-2 isopleth along the coast. However, the extent of the 99.9th percentile ERPG-2 isopleth is considerably less than the extent of the 100th percentile ERPG-2 isopleth towards the northwest of the intersection (where the terrain slopes are shallower).

If a less conservative approach is taken (depending on the wind direction), it is still recommended that the affected parts of the Austerville, Merewent and Treasure Beach residential areas; the affected parts of the Mobeni industrial area, Mondi Paper, the Engen and SAPREF oil refineries; and the affected schools, hospitals and clinics within the 99.9th percentile ERPG-2 isopleth be notified or possibly evacuated until the spill has been contained and removed.

5.5.5 The Avenue East – Refinery Drive intersection

- **Large Anhydrous Hydrogen Fluoride release**

Figure 5.21 presents isopleths indicating the downwind distances to the exposure limits: ERPG-2, IDLH and ERPG-3, respectively for an Anhydrous Hydrogen Fluoride release (1 kg/s emission rate) at The Avenue East – Refinery Drive intersection.

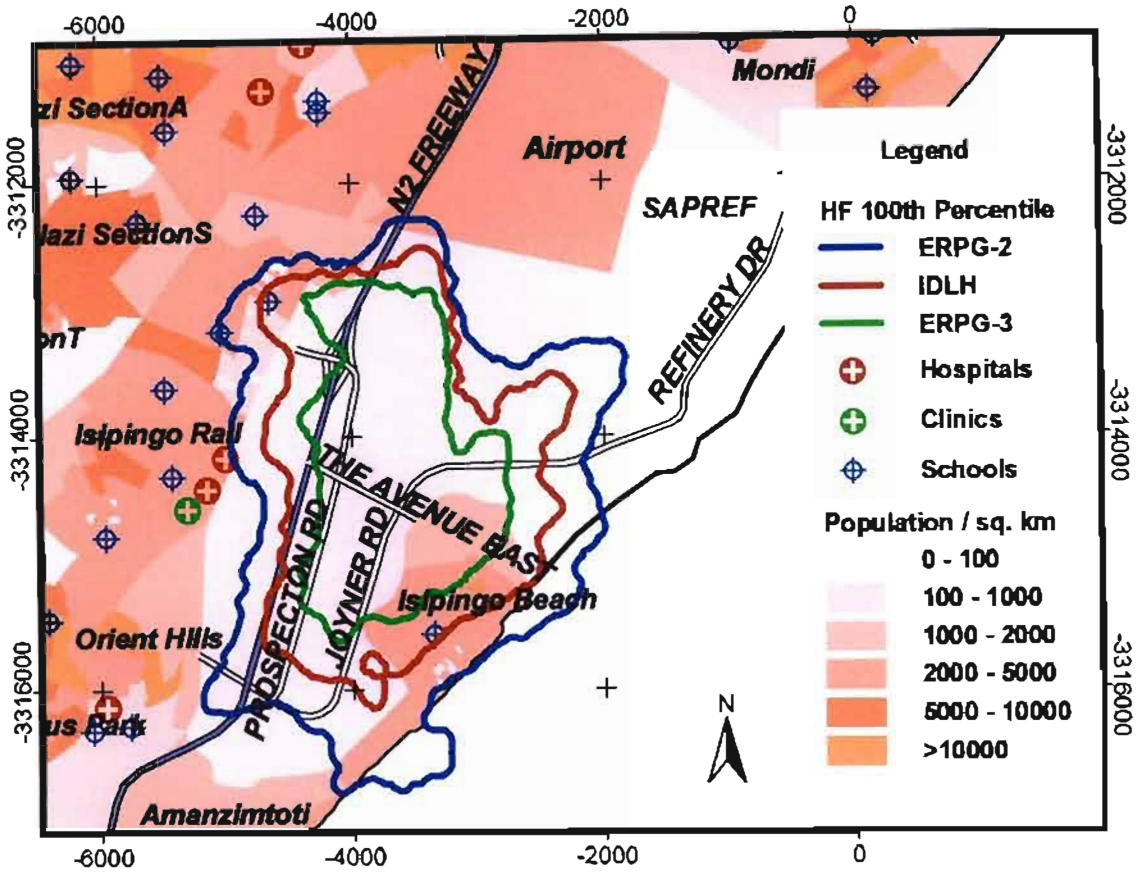


Figure 5.21: The extent of the impact on the area surrounding The Avenue East – Refinery Drive intersection of ground level concentrations following an Anhydrous Hydrogen Fluoride (HF) release (1 kg/s emission rate), using the ERPG and IDLH guidelines

Figure 5.21 indicates that concentrations of Anhydrous Hydrogen Fluoride above the ERPG-2 level may exist as far out as 2.2 kilometres from the intersection. The ERPG-2 isopleth in Figure 5.21 covers an area of 8.8 square kilometres. With the exception of Isipingo Beach, the residential population density is relatively low in the areas immediately surrounding The Avenue East – Refinery Drive intersection. Approximately 6100 residents within the ERPG-2 isopleth are potentially at risk, and if exposed would be expected to experience irreversible or other serious health effects that could impair their ability to take protective actions. Depending on the direction the wind is blowing towards, in the event of a large Anhydrous Hydrogen Fluoride release at The Avenue East – Refinery Drive intersection, it is recommended that the Isipingo Beach residential area; the affected parts of the Isipingo Rail and Prospecton industrial areas, the Durban International Airport, the SAPREF Oil Refinery; and the affected schools within the ERPG-2 isopleth, be notified or possibly evacuated until the spill has been contained and removed. Occupants of vehicles travelling on roads close to The Avenue

East – Refinery Drive intersection (e.g. N2 Freeway, Prospecton Road) may be exposed to high concentrations of Anhydrous Hydrogen Fluoride for short periods of time as they travel through and along the dispersing plume. Section 5.6 outlines the methodology that may be employed to investigate the health impact to road users, who are caught in queues that have formed on The Avenue East, Refinery Drive and Joyner Road as a result of an accident causing this release.

- **Worst-case Anhydrous Hydrogen Fluoride release**

A shipment of sixteen metric tons of Anhydrous Hydrogen Fluoride is transported to the SAPREF Oil Refinery monthly through The Avenue East – Refinery Drive intersection. Anhydrous Hydrogen Fluoride is transported in mild steel ISO-tainers or road tankers [de Klerk, 2004].

Consider the following release scenario:

- sixteen metric tons of Anhydrous Hydrogen Fluoride are released from an ISO-tainer
- these sixteen metric tons of Anhydrous Hydrogen Fluoride are released into the atmosphere over a one-hour period. This equates to a continuous emission rate of 4.4 kg/s.

Figure 5.22 presents isopleths indicating the downwind distance to the ERPG-3 exposure limit for an Anhydrous Hydrogen Fluoride release (4.4 kg/s emission rate) at The Avenue East – Refinery Drive intersection.

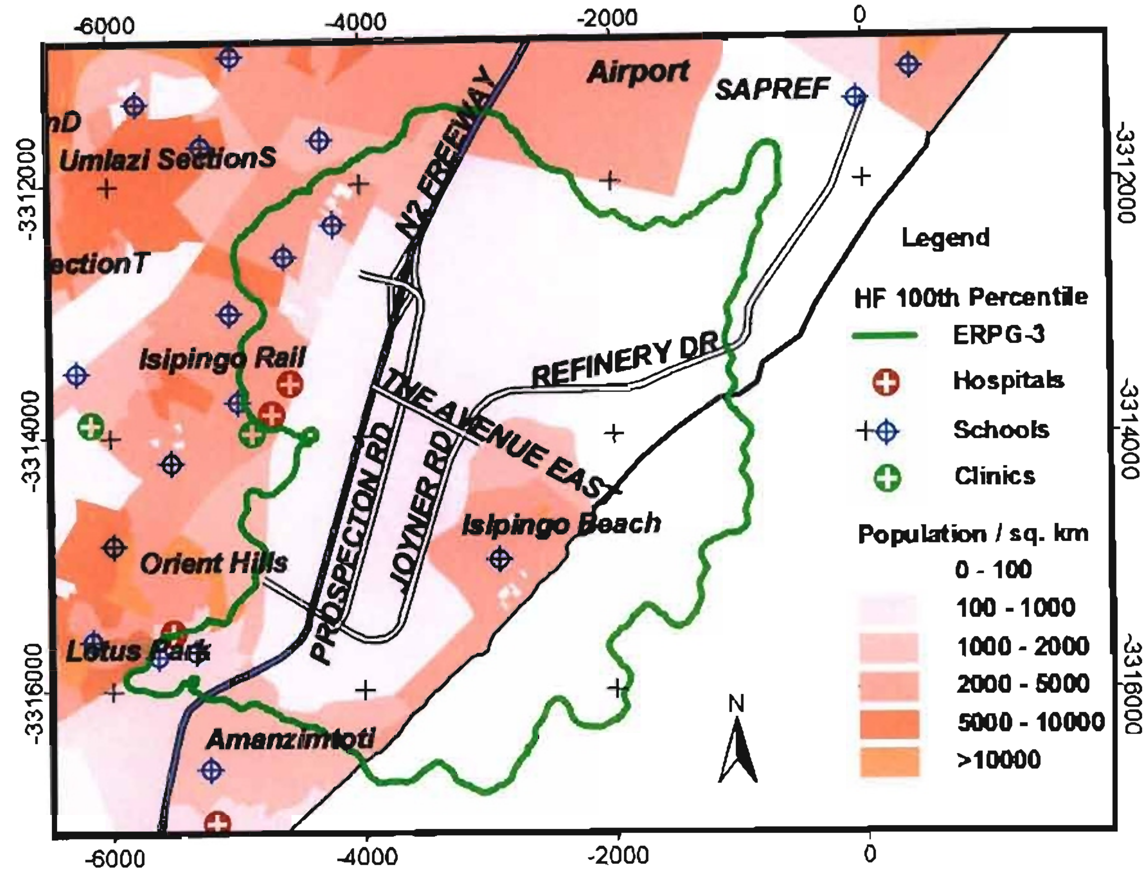


Figure 5.22: The extent of the impact on the area surrounding The Avenue East – Refinery Drive intersection of ground level concentrations following an Anhydrous Hydrogen Fluoride (HF) release (4.4 kg/s emission rate), using the ERPG-3 guideline

Figure 5.22 indicates that concentrations of Anhydrous Hydrogen Fluoride above the ERPG-3 level may exist as far out as 3.2 kilometres from the intersection. The ERPG-3 isopleth in Figure 5.22 covers an area of 16.1 square kilometres. Approximately eleven thousand residents within the ERPG-3 isopleth are potentially at risk, and if exposed would be expected to experience or develop life-threatening health effects. Depending on the direction the wind is blowing towards, in the event of a such a worst-case Anhydrous Hydrogen Fluoride release at The Avenue East – Refinery Drive intersection, it is recommended that Isipingo Beach, the affected parts of the Orient Hills, Lotus Park and Athlone Park residential areas; the affected parts of the Isipingo Rail and Prospecton industrial areas, the Durban International Airport, the SAPREF Oil Refinery; and the affected schools and hospitals within the ERPG-3 isopleth be evacuated until the spill has been contained and removed. The ERPG-2 and IDLH isopleths were not plotted as they extend beyond the output grid chosen in the ADMS™ simulation.

5.5.6 Summary of risk assessment results

The results of the risk assessment conducted in Sections 5.5.1 to 5.5.5 are summarised in Table 5.6.

Table 5.6: Impacts of selected dangerous goods releases at the chosen intersections

Intersection		**Dangerous substance released**	**Emission rate** [kg/s]	**Threshold** [100th percentile]	**Maximum threshold distance from source** [km]	**Area within threshold** [km^2]	**Residential population within threshold**
	Bayhead Road – South Coast Road	Acrylonitrile	1.0	ERPG-2	1.3	1.3	1720
		Acrylonitrile	3.3	ERPG-2	2.7	5.4	5743
	Edwin Swales VC Drive – South Coast Road	Acrylonitrile	1.0	ERPG-2	1.1	1.3	564
		Acrylonitrile	3.3	ERPG-2	3.3	5.3	5085
	M4 Southern Freeway – Duranta Road	Anhydrous Hydrogen Fluoride	1.0	ERPG-2	3.1	8.5	35049
	Tara Road – Duranta Road	Anhydrous Hydrogen Fluoride	1.0	ERPG-2	2.5	8.4	37402
	The Avenue East – Refinery Drive	Anhydrous Hydrogen Fluoride	1.0	ERPG-2	2.2	8.8	6136
		Anhydrous Hydrogen Fluoride	4.4	ERPG-3	3.2	16.1	11028

The ERPG-2 isopleth is generally accepted as the limit of emergency response [Brown et al. 2001]. The risk assessment results indicate that several thousands of residents are potentially at risk from experiencing irreversible or other serious health effects due to releases of dangerous goods at the selected intersections. In particular, large numbers of individuals living in close proximity to the M4 Southern Freeway – Duranta Road and Tara Road – Duranta Road intersections are potentially at risk from releases of Anhydrous Hydrogen Fluoride.

Only the impacts of Acrylonitrile and Anhydrous Hydrogen Fluoride releases have been highlighted in this chapter. Of the other Danger group I substances being transported through the selected intersections:

- Benzene and Isopropylamine have a relatively high IDLH value compared to the other selected chemicals (Table 5.3). Hence, the extent of the hazard area depicted will be smaller.
- Tetra Ethyl Lead has a very low vapour pressure (Appendix D: Table D.1) [NIOSH, 2002]. Thus, the rate of evaporation from a pool will be very low [Kawamura & Mackay, 1985] and the extent of the hazard area will be smaller.
- As discussed in Section 3.4.4, due to incorrect use of signage by the hauliers, there is some concern as to whether Methyl Isocyanate is actually being transported through the M4 Southern Freeway – Duranta Road and Tara Road – Duranta Road intersections. Nevertheless, graphical risk profiles for Methyl Isocyanate releases at the relevant intersections are presented in Appendix E.

5.6 Implications for Road Users

When demand exceeds capacity for a period of time on a roadway, a growing queue is formed. A releasing dangerous goods accident, which disrupts the normal flow of traffic at an intersection, is an example of a queuing process. Vehicles queue upstream of the intersection and their departure is delayed to a later instant in time. Queuing analysis may be combined with dispersion modelling to investigate the health impact to road users who are caught in such queues.

5.6.1 Traffic stream models

This section introduces certain concepts that are necessary for queuing analysis. May [1990] presented relationships among the fundamental traffic stream flow characteristics: flow, density and speed for a linear speed–density model. These relationships are illustrated in Figure 5.23.

Flow (q) is defined as the number of vehicles passing a specific point or through a particular section of roadway in a given time period. Flow is expressed as an equivalent hourly rate, often on a per lane basis (vehicles/hour/lane). Density (k) is defined as the number of vehicles occupying a roadway segment. Density is expressed on a per lane basis (vehicles/kilometre/lane). Speed is the average rate of motion expressed in units of kilometres per hour. Flow is exactly equal to the product of speed and density [May, 1990]. Hence:

$$q = u \times k \quad (5.2)$$

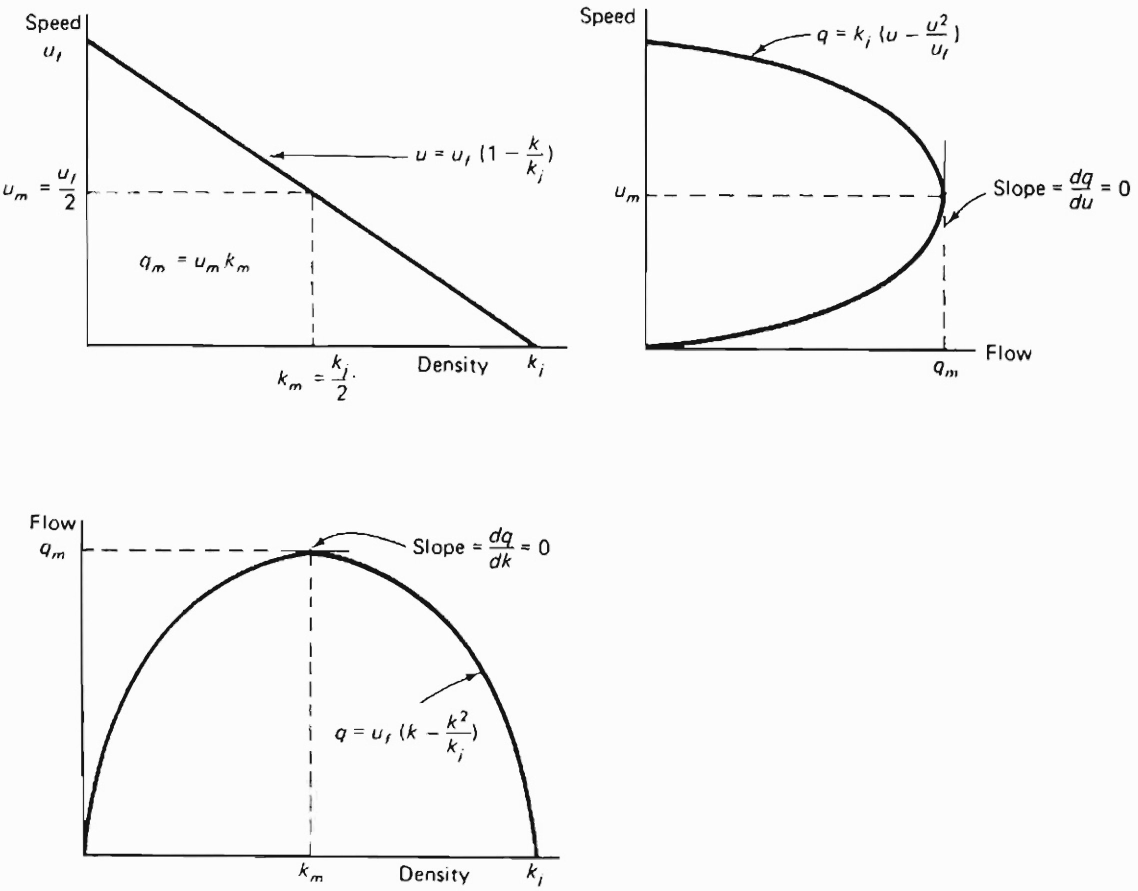


Figure 5.23: Relationships among the fundamental stream flow characteristics for a linear speed–density model [after May, 1990]

Several unique parameters are highlighted in Figure 5.23. These include:

- Maximum flow rate or *capacity* (q_m); the maximum sustainable flow rate at which vehicles reasonably may be expected to traverse a point or segment of roadway during a specified time period under given roadway, geometric, traffic and environmental conditions [TRB, 2000].
- Jam density (k_j). The density that exists when vehicles are bumper-to-bumper and stopped.
- Optimum density (k_m). The density that exists under conditions of maximum flow.
- Optimum speed (u_m). The speed that exists under conditions of maximum flow.

- Free-flow speed (u_f); in this context, the average speed of vehicles over an urban street segment without signalised intersections, under conditions of low volume [May, 1990].

5.6.2 Queuing Theory

May [1990] presented the following example to introduce the concepts of deterministic queuing analysis. Consider an accident (or incident) on a roadway that causes a reduction in capacity. The queuing diagram for this situation is presented in Figure 5.24. The input parameters are specified in Figure 5.24(a). The arrival rate of traffic upstream of the accident (λ) is given in vehicles per hour and is assumed constant for the study period. The normal service rate or capacity of uninterrupted flow (i.e. no accident) is designated in Figure 5.24 as μ, and is greater than the arrival rate. When the incident occurs, it reduces the service rate to μ_R, which is less than the arrival rate. This lower service rate is maintained for t_R hours, until the disabled vehicle causing the reduction in capacity has been removed.

Figure 5.24(b) drawn underneath the flow rate versus time diagram, is a diagram of cumulative vehicles (at a point) versus time. Horizontal lines in Figure 5.24(a), such as the arrival rate λ are transformed into sloping lines in Figure 5.24(b), with the slope equal to the magnitude of the flow rate.

The number of vehicles in the queue is represented by the vertical distance through the triangle in Figure 5.24(b). At the beginning of the incident, the number of vehicles in the queue is assumed to be zero, i.e. there is no initial queue. The queue increases to its maximum after t_R hours. After the disabled vehicle causing the reduction in capacity has been removed, the number of vehicles in the queue decreases until the normal service rate line intersects the arrival rate line. All vehicles arriving during the incident; as well as vehicles arriving after the disabled vehicle has been removed, but before the queue is dissipated; experience the queuing process and are forced to slow down significantly or stop. The horizontal distance across the triangle in Figure 5.24(b) represents individual *delay*. Delay refers to the additional travel time experienced by a road user as a consequence of the incident [May, 1990].

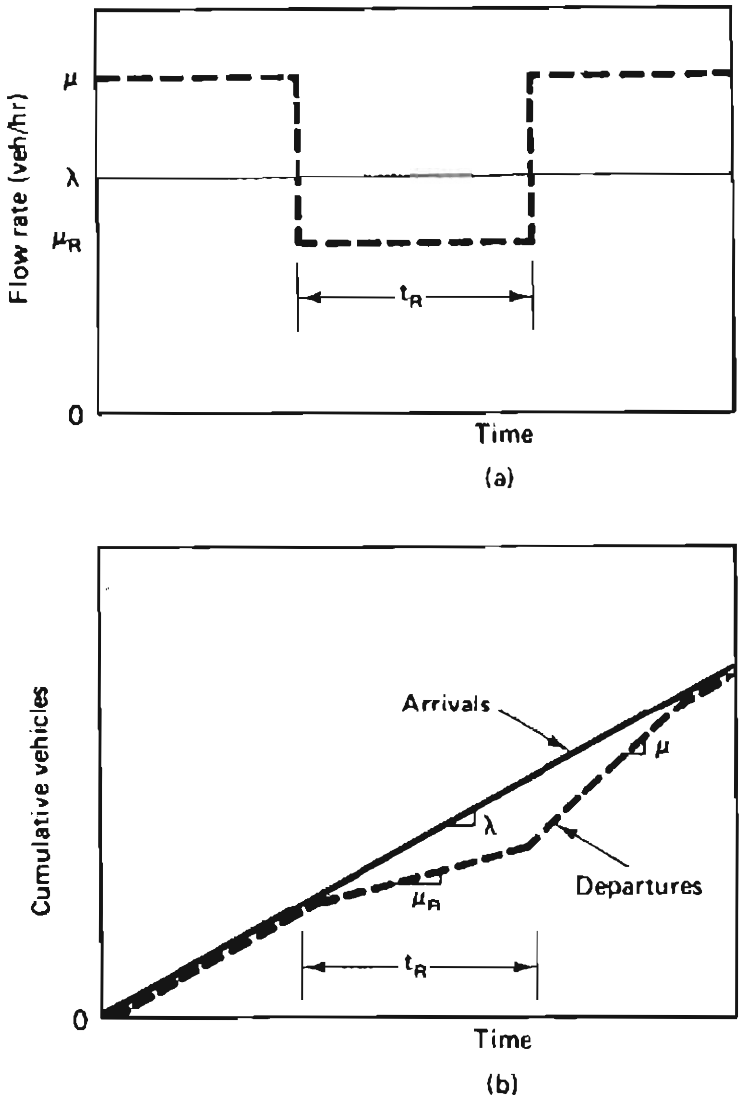


Figure 5.24: Queuing diagram for incident situation [after May, 1990]

May [1990] developed the following relationship to estimate the maximum number of vehicles in the queue at incident (or accident) sites:

$$Q_M = t_R \times (\lambda - \mu_R) \tag{5.3}$$

where:

Q_M = Maximum number of vehicles in the queue [vehicles]:

λ = Average arrival rate of traffic upstream of the incident [vehicles per hour]

μ_R = Reduced service rate during incident [vehicles per hour]

t_R = Duration of incident [hours]

The value of μ_R may be zero when the roadway is completely blocked, or some value (μ_R < λ) when the roadway is partially blocked by a disabled vehicle. The number of vehicles in the queue is a linear function of the incident duration t_R [May, 1990].

5.6.3 Hypothetical worst-case scenario for a dangerous goods release

The deterministic queuing analysis methods developed by May [1990] have been employed to investigate the health impact to road users as result of a releasing dangerous goods accident at an intersection. The greatest road-user health impacts will occur when a worst-case dispersion scenario coincides with a worst-case scenario from a traffic perspective. The Acrylonitrile release (3.3 kg/s emission rate) at the Edwin Swales VC Drive – South Coast Road intersection from Section 5.5.2 is used to illustrate the methodology adopted in this investigation.

The following hypothetical worst-case scenario from a traffic perspective is investigated:

- The heavy vehicle transporting Acrylonitrile is involved in an accident during either the morning or afternoon *peak hour.* The peak hour consists of the four consecutive fifteen-minute periods that have the highest demand volume of traffic during the study period [TRB, 2000]. The peak hour for different vehicle types occurs at slightly different times. However, analysis of the eThekwini Municipality traffic volume count at the Edwin Swales VC Drive – South Coast Road intersection conducted on 22 April 2002, indicates that heavy-vehicle traffic remains reasonable constant throughout the daylight hours. Hence, the peak hour for "all vehicles" was considered.
- The accident is of sufficient severity to result in a dangerous goods release and disable the vehicle.
- The accident occurs at the start of the peak and it takes emergency response personnel one hour to contain the spill and remove the disabled vehicle from the scene, i.e. t_R = 1 hour.
- There is no peaking of demand flows during the hour and vehicles arrive at a uniform rate during the peak.
- Traffic on the approach under investigation is unable to evacuate or be diverted from the road.
- The accident occurs within the intersection (for example, at the position demarcated "**X**" in Plate 5.1). The disabled vehicle, results in the through-lanes and

right-turn lanes of a particular approach (southern) being blocked. During the next phase of the traffic signal cycle, vehicles from the adjacent (eastern) approach will not be able to proceed straight. Eventually, all approaches will experience severe reductions in capacity, as vehicles from each approach are prevented from proceeding straight or turning right. Hence, queues will develop on all approaches.

- Plate 5.1 illustrates that the Edwin Swales VC Drive – South Coast Road intersection has left-turn *slip lanes* on all four approaches. The slip lanes are the turning movement lanes separated from the neighbouring lanes by triangular islands. For a limited period after the incident occurs, drivers may be able to utilise the left-turn slip lanes.
- Drivers, who are not within line of sight of the incident, will have no knowledge of the dangerous goods release. Hence, they will be unaware of the need to evacuate or bypass the area (by utilising the left-turn slip lanes) and will remain in their original lanes; the queues on each approach will continue to grow [Roebuck, 2005].
- The left-turn slip lanes are short lanes. Short lanes are lanes of limited length, e.g. a turn bay or part of a lane available downstream of parked vehicles [Akçelik & Associates, 2002]. Hence, once the queue extends beyond the position where the short lanes are generated, the entire approach (including the left-turn slip lanes) will become completely blocked [Roebuck, 2005]. The value of the reduced service rate during the incident μ_R, will then be zero.
- The concentration of Acrylonitrile in the immediate vicinity of the releasing accident will be extremely high (i.e. greater than four times the Immediately Dangerous to Life or Health concentration within one hundred metres of the source). A few minutes of exposure to these extremely high concentrations may result in the death of persons (including drivers) within this region [NIOSH, 2002; Ecoserv, 2003]. This factor may also contribute to the entire approach (including the left-turn slip lanes) becoming completely blocked.

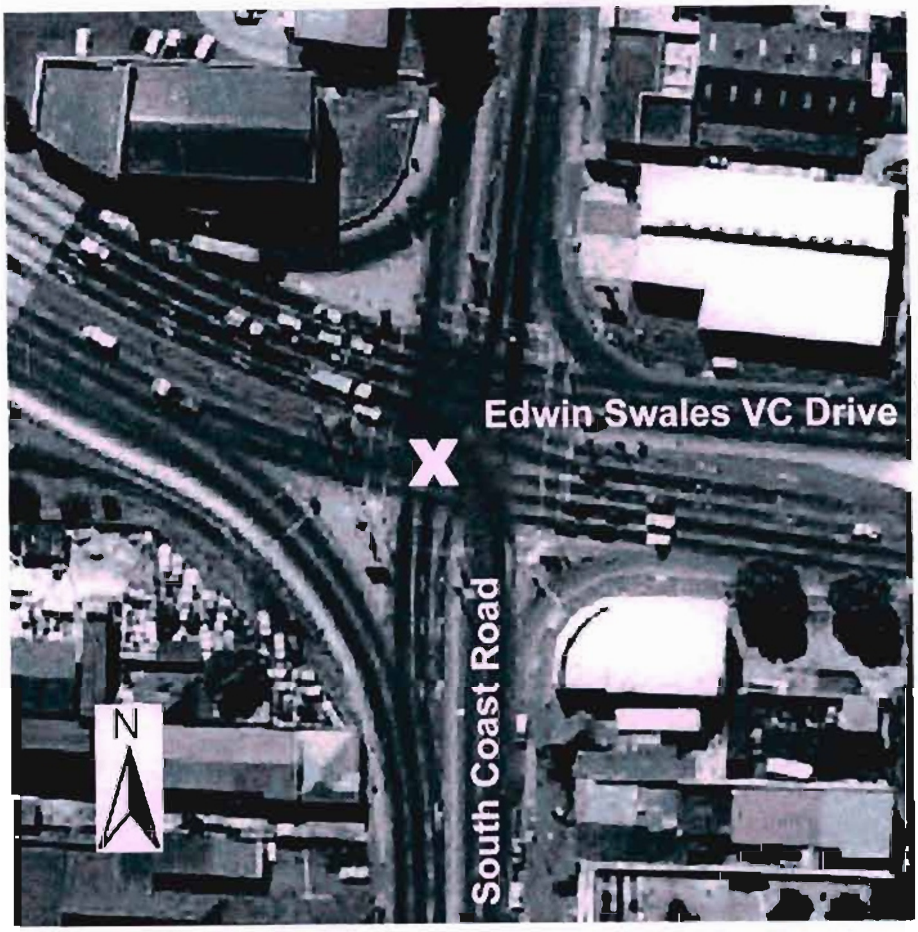


Plate 5.1: Layout of the Edwin Swales VC Drive – South Coast Road intersection [eThekwini Municipality GIS, 2005]

The greatest impact will occur when the prevailing winds cause the plume that has formed as a result of the Acrylonitrile release, to travel parallel to the road and in the same direction as the growing queue. The Edwin Swales VC Drive – South Coast Road intersection has four approaches. Hence, the prevalence of an adverse wind direction is four times as likely when compared to a releasing dangerous goods accident that occurs on a highway segment.

Section 5.2.3 reported that the predominant winds in the Durban South Basin blow from two sectors: the north, north-northeast and northeast sector; and south, south-southwest and southwest sector, in approximately equal proportions (30 per-cent each). That is, the predominant winds blow along South Coast Road. Analysis of the eThekwini Municipality traffic count for the intersection on 22 April 2002 indicated that both the morning and afternoon peak hour volumes on the southern approach were greater than the corresponding volumes on the northern approach. Accordingly, the methodology adopted in this investigation is illustrated by applying the hypothetical worst-case assumptions to a queuing analysis of the southern approach of the Edwin Swales VC Drive – South Coast Road intersection.

5.6.4 Queuing analysis

During the eThekwini Municipality traffic count for the intersection on 22 April 2002, 1883 vehicles were recorded arriving on the southern approach in the morning peak hour. The morning (AM) peak hour volume was greater than the afternoon (PM) peak hour volume on the southern approach. Hence, the average arrival rate of traffic upstream of the incident λ, is taken as 1883 vehicles per hour.

As discussed in Section 5.6.3:

- for the hypothetical worst-case traffic scenario under investigation, the reduced service rate of the approach during the incident μ_R, is taken as zero.
- the duration of incident t_R is assumed to be one hour.

Substituting these chosen values of λ, μ_R and t_R into Equation (5.3) yields:

$$\begin{aligned}&\textit{Maximum number of vehicles in the queue, } Q_M \\ &= t_R \times (\lambda - \mu_R) = 1 \times (1883 - 0) = 1883 \textit{ vehicles}\end{aligned}$$

A less conservative approach (which would not yield the worst-case traffic scenario) would be to assume that vehicles will be able to utilise the left-turn slip lanes for the entire duration of the incident. During this highly unlikely case [Roebuck, 2005], the reduced service rate of the approach μ_R, is taken as a function of the *saturation flow rate* of the left-turn slip lanes. The saturation flow rate is the maximum departure (queue discharge) flow rate achieved by vehicles departing from the queue during the green period at traffic signals [TRB, 2000]. The procedures described in the *Highway Capacity Manual* [TRB, 2000] may be applied to calculate the saturation flow rate of the left-turn slip lanes.

5.6.5 Application of traffic stream flow fundamentals

In order to estimate the maximum length of the queue, the relationships among the fundamental traffic stream flow characteristics (introduced in Section 5.6.1) are used.

Bowen-Jones [1995], investigating signalised intersections in Durban, estimated the jam density k_j to be 136 passenger car units per kilometre per lane. The assumption was made that this figure is representative of conditions within the Durban South Basin. In order to convert jam density k_j in units of *passenger car units per kilometre per lane*, into units of *vehicles per kilometre per lane*, the additional space occupied by heavy vehicles must be accounted for. The passenger-car equivalent used for each heavy vehicle is 2.0 passenger car units (pcu's) [TRB, 2000].

The following equation was employed to convert jam density k_j into units of vehicles per kilometre per lane:

$$k_{jVEH} = \frac{k_{jPCU}}{(HV \times E_{HV}) + (C \times E_C)} \tag{5.4}$$

where:

k_{jVEH} = Jam density in units of vehicles per kilometre per lane

k_{jPCU} = Jam density in units of passenger car units per kilometre per lane

HV = Proportion of heavy vehicles (and buses) on the approach

E_{HV} = Passenger-car equivalent of a heavy vehicle (or bus) = 2.0 pcu/heavy vehicle

C = Proportion of cars on the approach

E_C = Passenger-car equivalent of a car =1.0 pcu/car

Analysis of the eThekwini Municipality traffic count for the Edwin Swales VC Drive – South Coast Road intersection on 22 April 2002, indicates that heavy vehicles and buses comprise approximately 20 per-cent of the total traffic on the southern approach, with cars comprising the remainder. Substituting these parameters into Equation (5.4) yields the jam density k_{jVEH} in units of vehicles per kilometre per lane:

$$k_{jVEH} = \frac{k_{jPCU}}{(HV \times E_{HV}) + (C \times E_C)} = \frac{136}{(0.20 \times 2) + (0.80 \times 1)}$$

$$= 114 \text{ vehicles per kilometre per lane}$$

As an alternative to these computations, the actual jam density on each approach may be measured directly in the field.

Upstream of the intersection (i.e. before the flaring of the southern approach at the junction) two lanes are available for traffic flow on Edwin Swales VC Drive. The maximum length of the queue may be estimated using the following relationship:

$$Q_{ML} = \frac{Q_M}{k_{jVEH} \times N} \tag{5.5}$$

where:

Q_{ML} = Maximum queue length [kilometres]

Q_M = Maximum number of vehicles in the queue [vehicles]

k_{jVEH} = Jam density [vehicles per kilometre per lane]

N = Number of lanes on the approach upstream of the intersection [lanes]

Substituting the estimated parameters: Q_M, k_{jVEH} and N, into Equation (5.5) yields:

$$\textit{Maximum queue length, } Q_{ML}$$
$$= \frac{Q_M}{k_{jVEH} \times N} = \frac{1883}{114 \times 2} = 8.3 \textit{ kilometres}$$

5.6.6 Integration of queuing analysis and dispersion modelling

Through the use of GIS, plume coordinates have been integrated with the transportation network. For the Acrylonitrile release (3.3 kg/s emission rate) at the Edwin Swales VC Drive – South Coast Road intersection, concentrations above the ERPG-2 level may exist as far out as 1.4 km along the southern approach (Figure 5.17). The estimated maximum queue length (8.3 kilometres) is greater than the extent of the ERPG-2 isopleth. Hence, for the scenario under investigation, vehicles within the ERPG-2 isopleth along the southern approach are at jam density.

The short lanes on the southern approach provide additional queue storage potential. Using aerial photographs and GIS, this additional queue storage potential has been estimated to be equivalent to a single lane of length 230 metres. The number of queued vehicles within the ERPG-2 isopleth may be estimated using the following relationship:

$$Q_{ERPG-2} = \left(L_{ERPG-2} \times k_{jVEH} \times N\right) + \left(L_{SL} \times k_{jVEH}\right) \tag{5.6}$$

where:

Q_{ERPG-2} = Number of queued vehicles within the ERPG-2 isopleth [vehicles]

L_{ERPG-2} = Length of the approach within the ERPG-2 isopleth [kilometres]

L_{SL} = Additional queue storage potential of the short lanes [kilometres]

k_{jVEH} = Jam density [vehicles per kilometre per lane]

N = Number of lanes on the approach upstream of the intersection (i.e. before the flaring of the approach at the junction) [lanes]

Substituting the estimated parameters: L_{ERPG-2}, L_{SL}, k_{jVEH} and N, into Equation (5.6), yields the number of queued vehicles along the southern approach within the ERPG-2 isopleth:

$$\begin{aligned} Q_{ERPG-2} &= \left(L_{ERPG-2} \times k_{jVEH} \times N\right) + \left(L_{SL} \times k_{jVEH}\right) \\ &= \left(1.40 \times 114 \times 2\right) + \left(0.23 \times 114\right) = 346 \text{ vehicles} \end{aligned}$$

After a period t_R of one hour, there are Q_M number of vehicles in the queue. As discussed in Section 5.6.3, vehicles are assumed to arrive at a uniform rate during the peak. Hence, the time it takes for the queue to reach the ERPG-2 isopleth, t_{ERPG-2} may be simply estimated using the following relationship:

$$t_{ERPG-2} = \frac{Q_{ERPG-2}}{Q_M} \times 60 \tag{5.7}$$

where:

t_{ERPG-2} = Time it takes for the queue to reach the ERPG-2 isopleth [minutes]

Q_{ERPG-2} = Number of queued vehicles within the ERPG-2 isopleth [vehicles]

Q_M = Maximum number of vehicles in the queue (at t_R = 1 hour) [vehicles]

Substituting the estimated parameters: Q_{ERPG-2} and Q_M, into Equation (5.7), yields the time it takes for the queue along the southern approach to reach the ERPG-2 isopleth:

$$t_{ERPG-2} = \frac{Q_{ERPG-2}}{Q_M} \times 60 = \frac{346}{1883} \times 60 = 11 \text{ minutes}$$

Multiplying the estimated number of queued vehicles within the ERPG-2 isopleth by the average vehicle occupancy, yields an estimate of the number of affected road users within the ERPG-2 isopleth. Roebuck [2004] recommended that an average vehicle occupancy of two persons per vehicle be assumed. Hence, in the event of an Acrylonitrile release at the Edwin Swales VC Drive – South Coast Road intersection, approximately seven hundred road users within the ERPG-2 isopleth on the southern approach may experience irreversible or other serious health effects that could impair their ability to take protective actions.

The procedure outlined in Sections 5.6.4 to 5.6.6 has been utilised to estimate the number of affected road users within the ERPG-2 isopleth on the other approaches to the Edwin Swales VC Drive – South Coast Road intersection, in the event of a worst-case Acrylonitrile release. The results of this analysis are summarised in Table 5.7.

The worst-case scenario from a traffic perspective would be a dangerous goods release during the morning or afternoon peak hour. A worst-case dispersion scenario would involve a dangerous goods release during stable atmospheric conditions. Stable atmospheric conditions are often characteristic of clear, calm and dry winter nights [Preston-Whyte & Tyson, 1988]. Table 5.7 reveals that in the event that adverse dispersion and traffic conditions coincide with an Acrylonitrile release at the Edwin Swales VC Drive – South Coast Road intersection, up to 1100 road users may experience irreversible or other serious health effects that could impair their ability to take protective actions. Aggregating the risk on each approach reveals that approximately 3400 road users within the ERPG-2 isopleth are potentially at risk.

Table 5.7: Road users within the ERPG-2 isopleth: Acrylonitrile release (3.3 kg/s emission rate) at the Edwin Swales VC Drive – South Coast Road intersection

Parameter	Approach			
	North	South	East	West
Peak hour under investigation	PM	AM	PM	AM
Arrival rate of traffic upstream of the accident, λ [veh/hr]	1180	1883	1608	2786
Reduced service rate during incident, μ_R [veh/hr]	0	0	0	0
Duration of incident, t_R [hr]	1	1	1	1
Maximum number of vehicles in the queue, Q_M [veh] (5.3)	1180	1883	1608	2786
% Heavy vehicles (and buses) on approach, *HV*	27%	20%	12%	13%
Jam density, k_{jVEH} [veh/km/lane] (5.4)	107	114	121	120
# of lanes on approach upstream of intersection, *N*	2	2	3	5
Maximum queue length, Q_{ML} [km] (5.5)	5.51	8.29	4.43	4.64
Length of approach within ERPG-2 isopleth, $L_{ERPG\text{-}2}$ [km]	1.38	1.41	1.20	0.94
Additional queue storage potential of short lanes, L_{SL} [km]	0.20	0.23	0.27	0.04
Number of queued vehicles within ERPG-2 isopleth, $Q_{ERPG\text{-}2}$ [veh] (5.6)	318	346	467	569
Time taken for queue to reach ERPG-2 isopleth, $t_{ERPG\text{-}2}$ [min] (5.7)	16	11	17	12
Average vehicle occupancy [persons/veh]	2	2	2	2
Number of road users within ERPG-2 isopleth	635	691	934	1139

5.7 Why Dense Gas Effects Have Not Been Incorporated

The aim of this investigation is to illustrate how traffic and transportation techniques may be applied toward the issues of dangerous goods transportation. Less emphasis has been placed on dispersion modelling techniques. Certain dangerous goods releases will result in the formation of a gas cloud that has a density greater than the ambient air density. The higher density may occur for example, as a result of the molecular weight of the chemical or the low temperature at which the chemical is released [Van Ulden, 1988]. Releases of Acrylonitrile and Hydrogen Fluoride for example, may produce dense gas clouds under certain circumstances [NIOSH, 2002]. ADMS™ is incapable of modelling dense gas dispersion [CERC, 2001].

The influence of the density effects on dispersion is primarily due to the associated buoyancy forces. Negative buoyancy refers to a buoyancy force opposite to the positive direction of the z-coordinate. Thus, a dense gas layer at ground level in the atmosphere is defined to be a negatively buoyant flow. The converse is a positively buoyant flow such as an emission from a hot source into the atmosphere. The neutrally buoyant case is generally referred to as *passive* [Britter & McQuaid, 1988].

5.7.1 Complex terrain

The generally accepted and used dense-gas dispersion models such as DEGADIS [Spicer & Havens, 1989] and SLAB [Ermak, 1990] do not account for complex terrain. As topographical features were found to have a very significant effect on the hazard area, this factor contributed to the decision not to employ dense gas dispersion modelling. Moreover, DEGADIS and SLAB do not allow for long-term simulations and subsequent percentile calculations [Spicer & Havens, 1989; Ermak, 1990] such as those performed in this investigation.

5.7.2 Britter and McQuaid criteria

The Richardson number is a dimensionless number that is relevant to dense gas dispersion. It is the ratio of the buoyancy forces to the inertia forces of the flow. The Richardson number is the parameter that is used to establish whether a dense gas release will exhibit significant density effects or if it may be treated as a passive release for practical purposes. Britter & McQuaid [1988] advised that for continuous releases, the flow will be effectively passive from the source and passive dispersion results may be used when:

$$\left(\frac{g_o' \times Q_o}{D \times U_{ref}^3} \right)^{\frac{1}{3}} \leq 0.15 \tag{5.8}$$

where:

$$g_o' = g\left(\frac{\rho_o - \rho_a}{\rho_a}\right) = g\left(\frac{\rho_o}{\rho_a} - 1\right) \tag{5.9}$$

Q_o = volume flow rate from a ground-level source [m^3/s]

U_{ref} = mean wind velocity at reference height of 10 m [m/s]

D = characteristic horizontal source dimension [m]

ρ_o = density of the released material [kg/m^3]

ρ_a = density of the ambient air [kg/m^3]

g = acceleration due to gravity, 9.81 m/s^2

By inspection, wind speed U_{ref} has the greatest influence on governing passive behaviour.

The relative vapour density of Acrylonitrile, i.e. ρ_o/ρ_a is equal to 1.8 [NIOSH, 2002]. In the event that twenty kilolitres of Acrylonitrile are released from an ISO-tainer and form an unconfined pool on the ground:

- Britter and McQuaid's passive condition is satisfied for a 1kg/s Acrylonitrile emission rate when $U_{ref} \geq 1.5$ m/s. Analysis of the meteorological data for the period 1993–2002 has revealed that the wind speed was greater than 1.5 m/s for 94 per-cent of the record.
- Britter and McQuaid's passive condition is satisfied for a 3.3kg/s Acrylonitrile emission rate when $U_{ref} \geq 2.18$ m/s. Analysis of the meteorological data for the period 1993–2002 revealed that the wind speed was greater than 2.18 m/s for 77 per-cent of the record.

In these calculations, the maximum pool area and hence, the characteristic horizontal source dimension, D in Equation (5.8) were estimated by assuming that the released Acrylonitrile will spread uniformly over the spill area and will form an unconfined pool having an average depth of one centimetre, following the recommendations of Kawamura & Mackay [1985] and US-EPA [1999].

Britter & McQuaid [1988] advised that downstream of the source, the source size D becomes progressively less relevant as the plume forgets its history. Provided the concentrations of interest do not occur within the immediate vicinity of the source, e.g. within $5D$, the source size D is not significant.

5.7.3 Thermodynamics of Hydrogen Fluoride modelling

Under laboratory conditions, the relative vapour density of Anhydrous Hydrogen Fluoride is equal to 0.7 times that of air [NIOSH, 2002]. However, there are several complex interactions that influence the dispersion of a mixture of Hydrogen Fluoride (HF), air and water in a cloud that has formed as a result of an accidental release [Lines, 1995]. Oligomers of Hydrogen Fluoride include $(HF)_2$, $(HF)_6$ and $(HF)_8$. HF shows oligomerisation behaviour in the vapour phase and behaves as a dense gas in dry air. Dilution causes the endothermic dissociation of these HF oligomers; this increases the density of the dispersing cloud. Increasing the temperature also favours dissociation. However, dissociation decreases the mean molecular weight of the Hydrogen Fluoride causing a decrease in cloud density. HF present as an aerosol evaporates and the pollutant cloud cools; however, the volume increases causing a reduction in the overall cloud density [Lines, 1995].

Water vapour in the air and HF react exothermically to produce an acid mist, this increases the cloud temperature and reduces the density. HF releases may be modelled by dense gas dispersion. However, in moist air at a relative humidity greater than 50 per-cent, the effect of the interaction between HF and water reduces the downwind distance where the excess density is significant and may lead to positive buoyancy. In fact, Hydrogen Fluoride clouds are predicted to become buoyant at humidities greater than 67 per-cent [Lines, 1995]. The annual average humidity in Durban is 79 per-cent [Hunter, 1990]. Table 5.8 confirms that although the relative humidity in the basin varies diurnally and seasonally, the relative humidity rarely drops to levels at which a dispersing HF plume will behave as a dense gas.

Table 5.8: Seasonal and diurnal variation in relative humidity in Durban, 1993–2002

		Summer Day	Winter Day	Summer Night	Winter Night
Mean		73	66	85	82
Percentile	**0.1**	59	45	73	66
	0.2	64	52	78	73
	0.3	68	58	82	78
	0.4	70	62	84	81
	0.5	73	66	87	84

With these complex thermodynamics influencing the dispersion of an accidental release of Anhydrous Hydrogen Fluoride, approximating a release in the Durban South

Basin as a passive cloud, was considered to be more representative of reality than using dense gas dispersion modelling.

Moreover, the dispersion model ALOHA, introduced in Section 5.5.1, is able to model both dense gas and passive dispersion. The dense gas dispersion calculations used in ALOHA are based on those used in the *DEGADIS™* model [US-EPA, 1999b]. Experimentation has revealed that, when the user allows the model to choose, in most cases ALOHA uses passive dispersion to model Anhydrous Hydrogen Fluoride releases within the Durban South Basin.

Brown et al. [2001] conducted a quantitative risk assessment to estimate the risk on a national basis in the U.S. due to transportation of selected dangerous goods. The selected dangerous goods included Chlorine, Ammonia and Anhydrous Hydrogen Fluoride, all substances that may behave as dense gases upon release under certain circumstances. CASRAM (Chemical Accident Statistical Risk Assessment Model), which provided atmospheric dispersion estimates in the Brown et al. [2001] study, does not treat dense gas or complex-terrain effects.

5.8 Effects of Sheltering

The consequence analysis used in this study did not account for the fact that people are normally indoors and are thus partially protected from outdoor concentrations of toxic substances. This effect, called *sheltering*, impacts severe accidents more profoundly than less severe accidents. The exclusion of sheltering from the risk assessment is consistent with most related studies [Brown et al. 2001]. For example, sheltering was excluded in calculating Protective Action Distances for the *Emergency Response Guidebook* [USDOT, 2004]. Accordingly, the effect of sheltering on the occupants of motor vehicles was also not considered in this investigation.

The protection afforded by sheltering depends primarily on the building ventilation rate and to a lesser extent on the release duration and meteorology. Sheltering provides the greatest protection for short-duration releases and large releases that occur at night [Brown et al. 2001]. During such incidents, sheltering the population in relatively airtight buildings may reduce the number of people exposed to dangerous airborne concentrations by more than two orders of magnitude over the potential number that could be exposed if no sheltering occurs (i.e., when everybody is outdoors). Wellplanned emergency management procedures may further reduce dangerous goods transportation risk by advising all persons in the path of the plume to remain indoors, shut off ventilation systems and take steps to reduce infiltration into the building [Brown et al. 2001].

5.9 Chapter Summary

Dispersion modelling has been utilised to estimate the consequences of dangerous goods releases at the Bayhead Road – South Coast Road; Edwin Swales VC Drive – South Coast Road; Tara Road – Duranta Road; M4 Southern Freeway – Duranta Road; and The Avenue East – Refinery Drive intersections. ADMS™, the new generation dispersion modelling software used in this study, uses the Monin-Obukhov relationship to describe the condition of the atmosphere rather than the Pasquill stability categories. ADMS™ is capable of modelling complex terrain situations and estimating airflow and dispersion over hills. The unique topography of the Durban South Basin greatly influences the dispersion of contaminants. Complex and diverse interactions arise between wind speed, wind direction and the underlying terrain. Air dispersion modelling was undertaken to assess the site-specific effect of these interactions.

The dispersion of a neutrally buoyant gas was simulated at each of the five selected intersections using a continuous unit emission rate. These simulations were conducted using every hour of meteorological conditions for a four-year period, thus encapsulating all feasible wind directions and atmospheric stabilities. This ADMS™ output was scaled by a new emission rate and chemical-specific concentration conversion factor, in order to estimate downwind concentrations resulting from specific release scenarios. Through the use of this efficient methodology, downwind concentrations may be estimated for a passive release of any chemical at any emission rate, with only a single run of the dispersion model at a location.

Geographical information systems provide a natural platform for the analysis dangerous goods releases, enabling the integration of information describing the toxic plume co-ordinates, the transportation network and population distribution. The downwind concentrations estimated by ADMS™ for specific release scenarios, were compared to exposure guidelines, which relate the intensity of the concentration to the degree of injury. Taking the size of the impact area and using local population density information, allowed the number of people exposed to a threshold concentration of each chemical to be estimated. The dispersion modelling simulations indicate that several thousands of residents are potentially at risk from experiencing irreversible or other serious health effects due to releases of dangerous goods at the selected intersections. In particular, large numbers of individuals living in close proximity to the M4 Southern Freeway – Duranta Road and Tara Road – Duranta Road intersections are potentially at risk from releases of Anhydrous Hydrogen Fluoride.

Queuing analysis and traffic flow fundamentals may be integrated with the results of dispersion modelling to estimate the number of road users at risk from a releasing dangerous goods accident at an intersection. Applying this methodology to an Acrylonitrile release during peak traffic conditions at the Edwin Swales VC Drive – South Coast Road intersection, reveals that over a thousand road users may be exposed to concentrations that would cause irreversible or other serious health effects, which could impair their ability to take protective actions. The number of potential exposures in this investigation does not consider potential exposure reduction due to the protective effects of sheltering. Thus, the stated number of exposures represents a conservative upper bound on the actual number of injuries.

ADMS™ is incapable of modelling dense gas dispersion. However, releases of Acrylonitrile and Hydrogen Fluoride may produce dense gas clouds under certain circumstances. The widely used dense-gas dispersion models do not account for complex terrain. As topographical features were found to have a very significant effect on dispersion within the study area, this factor contributed to the decision not to employ dense gas dispersion modelling. Moreover, most dense-gas dispersion models do not allow for long-term simulations such as those conducted in this investigation. Application of the Britter & McQuaid [1988] criteria revealed that passive dispersion results are valid for the majority of the simulated Acrylonitrile releases. Due to complex thermodynamics specific to Hydrogen Fluoride, passive dispersion results are more applicable for HF releases within the Durban South Basin.

CHAPTER 6

6. CONCLUSIONS

6.1 Summary of Investigation

In this investigation, a methodology was developed to estimate the likelihood and consequences of releases of dangerous goods due to road accidents at intersections. A case study was explored and the methodology was applied to estimate the risks posed to the people residing in, working in and travelling through the Durban South Basin.

In Chapter 2, the literature pertaining to risk assessment of dangerous goods transport is reviewed. The current state of the art and the theory and methodology used in previous risk analyses are identified. In Chapter 3, the selection of the case study for this investigation is discussed. An account is given of the traffic surveys conducted at the following intersections: Bayhead Road – South Coast Road; Edwin Swales VC Drive – South Coast Road; Tara Road – Duranta Road; M4 Southern Freeway – Duranta Road; and The Avenue East – Refinery Drive. Chapter 4 presents two approaches to estimate the likelihood of dangerous goods accidents and releases at intersections: a deterministic model and a method based on Monte Carlo simulation. Chapter 5 discusses the integration of dispersion modelling and geographic information systems in order to estimate the impacts of releasing dangerous goods accidents at the selected intersections; as well as the use of queuing analysis to estimate the risks posed to road users.

6.2 Summary of Findings

The findings of the literature review and the risk assessment are discussed in this section.

6.2.1 Literature review

- The majority of the dangerous goods transportation studies reported in the literature relate to aspects such as risk analysis, database development and designating routes for transporting dangerous goods.
- Historical records confirm that dangerous goods transportation incidents may have very serious consequences.
- Dangerous goods releases may occur during normal transport (en-route) or as a result of a traffic accident. Traffic accidents are the leading cause of severe dangerous goods incidents (deaths, injuries, etc.).
- Risk is a measure of relative safety and is a combination of accident likelihood, release probability and consequence of release.
- Risk estimates are not precise. The accuracy of the risk estimates is governed by the quality of the data collected by disparate agencies and the judgements of the researcher.
- Risk estimation requires information on: flows of dangerous goods; incidents and accidents; and the population at risk.
- Accident likelihood is estimated from traffic accident rates and traffic volumes.
- An accident involving a dangerous goods vehicle cannot lead to potentially catastrophic consequences unless the cargo is released. The probability of a release, varies with the type of accident and varies between different classes of roads.
- Intensive risk analyses should consider the activities of non-residential areas and vulnerable zones (places that concentrate a large amount of people who are difficult to protect or evacuate, e.g. schools, hospitals or commercial centres).
- South African legislation stipulates that municipalities and provinces must prepare transport plans for the movement of dangerous goods by road along designated routes.

6.2.2 Case study

- High levels of traffic flow occur within the Durban South Basin and significant volumes of dangerous goods are transported on the roads of the basin daily.
- These high flows of dangerous goods, when combined with South Africa's poor road safety record, create numerous opportunities for incidents (including traffic

accidents) that could release dangerous goods into the environment and result in public exposure to poisonous, corrosive and possibly carcinogenic substances.

- In South Africa, the majority of road accidents occur in urban areas and accidents at intersections account for a high percentage of the total number of urban accidents.
- Dangerous goods accidents involving heavy vehicles may have far more severe consequences than those involving light delivery vehicles, due to the larger quantities of dangerous goods involved.
- Acrylonitrile, Anhydrous Hydrogen Fluoride, Benzene, Isopropylamine, Methyl Isocyanate and Tetra Ethyl Lead, all dangerous goods belonging to Danger group I (substances that present a very severe risk), are being transported through the following intersections: Bayhead Road – South Coast Road; Edwin Swales VC Drive – South Coast Road; Tara Road – Duranta Road; M4 Southern Freeway – Duranta Road; and The Avenue East – Refinery Drive.

6.2.3 Likelihood of dangerous goods accidents and releases

- The deterministic approach developed to estimate dangerous goods accident and release rates at intersections, reveals that the Edwin Swales VC Drive – South Coast Road intersection has the highest expected rate of dangerous goods accidents and releases, followed by the Bayhead Road – South Coast Road intersection. The Edwin Swales VC Drive – South Coast Road intersection is expected to experience, on average: six dangerous goods accidents per year and one releasing dangerous goods accident every thirteen months. The Tara Road – Duranta Road, M4 Southern Freeway – Duranta Road and The Avenue East – Refinery Drive intersections have a comparatively lower expected *Dangerous Goods Accident Rate* and *Dangerous Goods Releasing Accident Rate*. No reliable South African dangerous goods incident statistics are available to validate these results.
- The substances allocated to Danger group I, which are being transported through the selected intersections, present a very severe risk. However, as the proportion of heavy vehicles transporting these substances is low (compared to Petroleum for example), the estimated frequency of accidents and releases involving Danger group I substances is much lower.
- At the Edwin Swales VC Drive – South Coast Road intersection, the mean values of the *Dangerous Goods Accident Rate* and the *Dangerous Goods Releasing*

Accident Rate calculated using Monte Carlo simulation, are quite similar to those results calculated using the deterministic approach. However, Monte Carlo simulation enables a more detailed understanding of the nature and distribution of dangerous goods accident and releases.

6.2.4 Consequences of dangerous goods releases

- The ground-level concentrations resulting from a release of contaminants are dependent on the prevailing meteorological conditions.
- By combining information on the spill characteristics, material properties and meteorological and topographical parameters, the consequences of dangerous goods releases may be estimated using dispersion modelling.
- Long-term dispersion modelling simulations i.e. greater than one year, encapsulate all feasible wind directions and atmospheric stabilities at a location.
- The unique topography of the Durban South Basin greatly influences the dispersion of contaminants.
- The downwind concentrations estimated by the dispersion model may be compared to public exposure guidelines, which relate the intensity of the concentration to the degree of injury.
- The use of geographic information systems (GIS) enhances dispersion modelling by allowing consequences and population exposure to be estimated more efficiently. With GIS, information describing the transportation network, specific chemicals, historical meteorological conditions and population distribution may be combined into an integrated environment.
- Queuing analysis and traffic flow fundamentals may be integrated with dispersion modelling to estimate the number of road users at risk from a releasing dangerous goods accident at an intersection.
- The results of this investigation indicate that thousands of residents within the Durban South Basin are potentially at risk due to releases of dangerous goods at the selected intersections. In particular, over 35000 individuals living in close proximity to the M4 Southern Freeway – Duranta Road and Tara Road – Duranta Road intersections are potentially at risk from experiencing irreversible or other serious health effects due to releases of Anhydrous Hydrogen Fluoride.
- An Acrylonitrile release during peak traffic conditions at the Edwin Swales VC Drive – South Coast Road intersection may expose over a thousand road users to

concentrations that would cause irreversible or other serious health effects that could impair their ability to take protective actions.

- Application of the Britter & McQuaid [1988] criteria revealed that passive dispersion results are valid for the majority of the simulated Acrylonitrile releases. Due to complex thermodynamics specific to Hydrogen Fluoride, passive dispersion results are more applicable for HF releases within the Durban South Basin.
- The emergency response in the event of a large dangerous goods release should be to notify the affected communities and possibly evacuate the affected areas until the hazard has been contained and removed. If evacuation is not possible, sheltering the population in relatively airtight buildings may reduce the number of people exposed to toxic concentrations by more than two orders of magnitude over the potential number that could be exposed if no sheltering occurs (i.e., when everybody is outdoors).

6.3 Conclusions

The methodology developed in this investigation yields an estimate of the following:

- The likelihood or frequency of dangerous goods accidents and releases at intersections
- The extent of the impact area and the severity of the human consequences that may occur following releases of dangerous goods.

From the findings listed in Section 6.2, the following can be concluded:

Traffic surveys at selected locations (or along a route) provide an indication of directional dangerous goods vehicle flows and the types of dangerous goods being transported through these locations (or along these routes), i.e. traffic surveys are an acceptable means of hazard identification. However, the estimate of the hazard would be improved through the co-operation of industry within the study area.

The Monte Carlo simulation approach may be applied to a broad range of problems including the estimation of dangerous goods transportation risks, especially when there are substantial data uncertainties. Monte Carlo simulation enables a detailed understanding of the nature and distribution of the parameter being investigated. Utilising the same raw data as a deterministic approach, coupled with reasonable assumptions based on the available data, Monte Carlo simulation provides the researcher with far more information.

Complex and diverse interactions arise between wind speed, wind direction and the underlying terrain. Topographical features may have a significant impact on the extent of the hazard area. In such situations a dispersion model that is capable of incorporating complex terrain effects and estimating airflow and dispersion over hills, is required.

Through the use of the methodology developed in this investigation, downwind concentrations may be estimated for a passive release of any chemical at any emission rate, with only a single run of the dispersion model at a specific location. The output from simulations of the dispersion of a neutrally buoyant gas using a continuous unit emission rate, may be scaled by a new emission rate and chemical-specific concentration conversion factor, in order to estimate downwind concentrations resulting from specific release scenarios.

Dispersion modelling in combination with geographical information system enables an efficient estimation of the consequences of dangerous goods releases. Geographical information systems provide a natural platform for the analysis dangerous goods releases, enabling the integration of information describing the toxic plume co-ordinates, the transportation network and population distribution. Queuing analysis in combination with dispersion modelling and GIS is an applicable method for estimating the risk to users from releasing dangerous goods accidents at intersections.

The results of this risk assessment suggest that although dangerous goods accidents and releases within the Durban South Basin are infrequent, the potential exists for very serious incidents involving large numbers of casualties.

6.4 Recommendations and Suggestions for Future Work

6.4.1 Application of the methodology

Major Hazard Installations (MHI's) have an influence on the dangerous goods flows on the surrounding transportation network. It is envisaged that this document will alert risk analysts to the implications of dangerous goods transportation, and that such impacts will be included in future MHI risk assessments.

6.4.2 South African dangerous goods statistics

There is a need to develop and maintain reliable databases for analysing the movement of dangerous goods in South Africa. Databases should contain information on: shipment origin-destination, material type, quantity, route, shipper, haulier and shipment date.

There is also a need to develop and maintain databases that provide a thorough and accurate account of each dangerous goods incident in South Africa. The following data fields could be included in these databases:

- The chemical released in the incident.
- The quantity of material being transported in the shipment and the quantity of material released in each dangerous goods incident. This value would improve discharge fraction statistics.
- For incidents involving releases from bulk containers that are cracked or ruptured as a result of an accident, cataloguing the approximate size and location of the resulting hole would be helpful to future researchers.
- The approximate release duration would be a valuable statistic, as this is one of the primary factors in estimating the rate of emission into the atmosphere.
- A database containing photographs of accident scenes, failed containers, and release-related environmental and property damage would also beneficial. Due to advances in computer storage, such a database could be easily assembled, maintained and stored [Brown et al. 2001].

6.4.3 Enhancements to the proposed methodology

The proposed methodology could be enhanced by developing a *statistical* risk assessment model (or obtaining and modifying *CASRAM*, which is introduced in Section 5.7.3) to estimate dangerous goods release rates and dispersion. Distributions of impact areas could be generated stochastically through Monte Carlo sampling of accident and meteorological parameters. Hence, the *distribution* of possible outcomes could be identified, thereby allowing the probability of a particular consequence to be estimated.

For example, the release rate of material from the transport container may be based on the location and size of the hole, which follow distributions derived from dangerous goods incident databases. Total release amounts may follow discharge fraction distributions derived from incident databases [Brown et al. 2001].

6.4.4 Application of Intelligent Transportation Systems

The application of Intelligent Transportation Systems (ITS) to dangerous goods incidents warrants investigation. Intelligent transportation systems are emerging transportation technologies that enhance the safety and efficiency of vehicles and roadway systems. ITS include any technology that allows drivers and traffic control system operators to collect and use real-time information to improve roadway system control, vehicle navigation, or both [TRB, 2000]. Consider the Edwin Swales VC Drive – South Coast Road intersection, which experiences an average of four traffic accidents per week (Table 3.4). Electronic signboards placed before junctions (i.e. off-ramps, on-ramps, intersections, etc) on South Coast Road and Edwin Swales VC Drive, may be used to inform drivers to bypass the Edwin Swales VC Drive – South Coast Road intersection if an accident occurs there. In the event of a dangerous goods release, ITS may be used to instruct drivers on alternative routes to be used (so as to avoid exposure to any toxic plume) [Roebuck, 2005].

A. APPENDIX A: Preliminary Dangerous Goods Survey

A summary of the preliminary dangerous goods survey is presented in Table A.1.

Table A.1: Dangerous goods identified during the preliminary survey

UN No.	Dangerous Goods	Class	Danger Group	Location			
				Tara Road	The Avenue East	Bayhead Road	Lansdowne Road
1075	Liquefied petroleum gases	2	-		√		
1090	Acetone	3	II			√	
1105	Amyl alcohols	3	II/III			√	
1114	Benzene	3	I	√	√		
1120	Butanols	3	II/III			√	
1170	Ethyl alcohol	3	II/III			√	
1202	Diesel fuel	3	III		√		
1203	Petrol	3	II	√	√	√	
1210	Printing ink, flammable	3	II/III		√		
1223	Kerosene	3	III	√		√	
1230	Methanol	3	II			√	
1245	Methyl isobutyl ketone (hexone)	3	II			√	
1247	Methyl methacrylate monomer	3	II			√	
1263	Paint related material	3	II/III				√
1268	Petroleum products	3	I/II/III	√		√	
1274	Propyl alcohol, normal	3	II/III			√	
1294	Toluene	3	II			√	
1307	Xylenes	3	II/III				
1547	Aniline	6	II			√	
1649	Tetra Ethyl Lead	6	I		√		
1824	Sodium hydroxide solution	8	II/III	√		√	
1863	Aviation fuel	3	II/III			√	
1977	Nitrogen, refrigerated liquid	2	-			√	
1993	Additives, for petrol mixed with flammable solvent, non toxic	3	II			√	
1999	Tars, liquid	3	II/III	√	√	√	
2055	Styrene monomer inhibited	3	III		√	√	
2078	Toluene diisocyanate	6	II			√	
2672	Ammonia solution	8	III	√			
3082	Environmentally hazardous substance, liquid	9	III	√		√	
	Multiload*				√	√	√

**Multiload* refers to a vehicle carrying more than one type of dangerous substance. In place of the usual UN Number, the placard reads: "Multiload".

B. APPENDIX B: Dangerous Goods Intersection Surveys

B.1 Bayhead Road - South Coast Road Intersection Survey

A summary of the dangerous goods survey at the Bayhead Road - South Coast Road intersection is presented in Table B.1.

Date: 11/7/2004 Time: 07:55-13:55 Hours: 6 hours

- **Guidance on reading Table B.1**

Explanation of column headings:

NL: vehicle approaching the intersection from the NORTH, turned LEFT at the intersection

NS: vehicle approaching the intersection from the NORTH, proceeded STRAIGHT through the intersection

NR: vehicle approaching the intersection from the NORTH, turned RIGHT at the intersection

Similar conventions are used for vehicles approaching from the South, East and West.

Taking the first row of data in Table B.1 as an example, during the six hours surveyed:

- ONE dangerous goods heavy vehicle carrying an ISO-tainer of Butylene approached the Bayhead Road - South Coast Road intersection from the NORTH along South Coast Road and proceeded STRAIGHT through the intersection
- ONE dangerous goods heavy vehicle carrying an ISO-tainer of Butylene approached the Bayhead Road - South Coast Road intersection from the SOUTH along South Coast Road and turned RIGHT at the intersection

Table B.1: Summary of dangerous goods survey at the Bayhead Road - South Coast Road intersection

UN No.	Dangerous Goods	Class	Danger Group	Config-uration	South Coast Road						Bayhead Road			Σ
					From North			From South			From East			
					NL	NS	NR	SL	SS	SR	EL	ES	ER	
1012	Butylene	2.1	-	ISO-tainer		1				1				**2**
1075	Liquefied Petroleum Gases	2.1	-	HGV						1				**1**
1075	Liquefied Petroleum Gases	2.1	-	LDV	1	1			1	1	1		2	**7**
1093	Acrylonitrile, Inhibited	6.1	I	ISO-tainer						1	1			**2**
1114	Benzene	3	I	Tanker						1				**1**
1120	Butanols	3	II/III	Tanker						2	3			**5**
1170	Ethyl alcohol (Ethanol)	3	II/III	Tanker						1				**1**
1170	Ethyl alcohol (Ethanol)	3	II/III	ISO-tainer						1	5			**6**
1170	Ethyl alcohol (Ethanol)	3	II/III	Container	2									**2**
1173	Ethyl Acetate	3	II	Tanker						1				**1**
1199	Furfural	3	III	Tanker						2	2			**4**
1202	Diesel fuel	3	III	Tanker		1			1				1	**3**
1203	Petrol	3	II	Tanker	26	1			1	36	44		14	**122**
1208	Hexanes	3	II	Tanker							1			**1**
1212	Isobutanol	3	III	Tanker							3			**3**
1219	Isopropanol	3	II	Tanker						1				**1**
1221	Isopropylamine	3	I	ISO-tainer						1				**1**
1223	Kerosene	3	III	Tanker						2	2			**4**
1247	Methyl methacrylate monomer, inhibited	3	II	Tanker						2	1			**3**
1247	Methyl methacrylate monomer, inhibited	3	II	ISO-tainer							2			**2**
1263	Paint related material	3	II/III	LDV						2	1		2	**5**
1268	Petroleum products	3	I/II/III	Tanker					1	4	8			**13**
1268	Petroleum products	3	I/II/III	LDV							1			**1**
1274	n-Propanol	3	II/III	Tanker						1				**1**
1307	Xylenes	3	II/III	Tanker						2	5			**7**

UN No.	Dangerous Goods	Class	Danger Group	Config-uration	South Coast Road						Bayhead Road			Σ
					From North			From South			From East			
					NL	NS	NR	SL	SS	SR	EL	ES	ER	
1547	Aniline	6.1	II	ISO-tainer	1									1
1649	Tetra Ethyl Lead	6.1	I	Tanker							1			1
1823	Sodium hydroxide solid	-	-	Tanker	1									1
1824	Sodium hydroxide solution	8	II/III	Tanker		1			2					3
1863	Aviation fuel	3	II/III	Tanker						3	1			4
1866	Resin Solution, flammable	3	II/III	Container	2									2
1917	Ethyl Acrylate, inhibited	3	II	Tanker						1	1			2
1999	Tars, Liquid, including road asphalt and oils	3	II/III	Tanker						3	5			8
2055	Styrene monomer inhibited	3	III	Tanker						4	2			6
2218	Acrylic Acid, inhibited	8	II	Container						1				1
2282	Hexanols	3	III	Tanker						1	1			2
2348	Butyl Acrylate	3	III	Tanker						1				1
3082	Environmentally hazardous substance, liquid	9	III	Tanker	3					3	1			7
3082	Environmentally hazardous substance, liquid	9	III	ISO-tainer							1			1
3082	Environmentally hazardous substance, liquid	9	III	HGV						1	1			2
3265	Corrosive liquid, acidic, organic	8	I/II/III	Container						1				1
3295	Hydrocarbons, liquid	3	I/II/III	Tanker							1			1
	Multiload*			Tanker						2	1			3
	Multiload			HGV	2	2			1	1	2			8
	Multiload			LDV	3	1			1	11	3		15	34
Σ					**41**	**8**			**8**	**96**	**101**		**34**	**288**

**Multiload* refers to a vehicle carrying more than one type of dangerous substance. In place of the usual UN Number, the placard reads: "Multiload".

B.2 Edwin Swales VC Drive – South Coast Road Intersection Survey

A summary of the dangerous goods survey at the Edwin Swales VC Drive – South Coast Road intersection is presented in Table B.2.

Date: 31/10/2004 Time: 07:40-13:40 Hours: 6 hours

Table B.2: Summary of dangerous goods survey at the Edwin Swales VC Drive – South Coast Road intersection

UN No.	Dangerous Goods	Class	Danger Group	Config.	Edwin Swales VC Drive						South Coast Road						Σ
					From West			From East			From North			From South			
					WL	WS	WR	EL	ES	ER	NL	NS	NR	SL	SS	SR	
1073	Oxygen, Refrigerated liquid	2.2	-	Tanker		1											**1**
1075	Liquefied Petroleum Gases	2.1	-	Tanker		1				1				2		1	**5**
1075	Liquefied Petroleum Gases	2.1	-	HGV	1	3	1	1				1	2	1			**10**
1075	Liquefied Petroleum Gases	2.1	-	LDV		3	1									1	**5**
1090	Acetone	3	II	Tanker	1						1	1					**3**
1120	Butanols	3	II/III	Tanker							2	3			3	1	**9**
1123	Butyl Acetates	3	II/III	Tanker											1		**1**
1133	Adhesives containing flammable liquid	3	II/III	Tanker		1											**1**
1170	Ethyl alcohol (Ethanol)	3	II/III	Tanker	5	1	1				1	1		1		1	**11**
1170	Ethyl alcohol (Ethanol)	3	II/III	ISO-tainer											1		**1**
1170	Ethyl alcohol (Ethanol)	3	II/III	Container											1		**1**
1188	Ethylene Glycol Monomethyl Ether	3	III	Tanker								1			1		**2**
1193	Ethyl Methyl Ketone	3	II	Tanker							1						**1**
1199	Furfural	3	III	Tanker							1				1		**2**
1202	Diesel fuel	3	III	Tanker	1	3					1				1		**6**
1203	Petrol	3	II	Tanker	13	12	4	3	2	2	19	4	29	19	18	4	**129**
1221	Isopropylamine	3	I	ISO-tainer	1												**1**
1223	Kerosene	3	III	Tanker		1					2			1			**4**

UN No.	Dangerous Goods	Class	Danger Group	Config.	Edwin Swales VC Drive						South Coast Road						Σ
					From West			From East			From North			From South			
					WL	WS	WR	EL	ES	ER	NL	NS	NR	SL	SS	SR	
1245	Methyl isobutyl ketone (hexone)	3	II	Tanker	2												**2**
1263	Paint related material	3	II/III	Tanker											1		**1**
1268	Petroleum products	3	I/II/III	Tanker	1	2	1		3	1	3		2		2		**15**
1274	n-Propanol	3	II/III	Tanker	1						1				1		**3**
1301	Vinyl Acetate, Inhibited	3	II	Tanker							1						**1**
1307	Xylenes	3	II/III	Tanker							1				1		**2**
1350	Sulphur	4.1	III	Container		1					2				2		**5**
1649	Tetra Ethyl Lead	6.1	I	Tanker							1				1		**2**
1824	Sodium hydroxide solution	8	II/III	Tanker		1							1	1	2		**5**
1863	Aviation fuel	3	II/III	Tanker	1	3				2	1	1	2	1	1		**12**
1866	Resin Solution, flammable	3	II/III	Tanker						1							**1**
1866	Resin Solution, flammable	3	II/III	ISO-tainer											1		**1**
1992	Flammable liquid, toxic	3	I/II/III	HGV		1											**1**
1993	Additives, for petrol mixed with flammable	3	II	Tanker		1											**1**
1993	solvent	3	II	HGV									1				**1**
1999	Tars, Liquid, including road asphalt and oils	3	II/III	Tanker			1				1	1		1		1	**5**
1999	Tars, Liquid, including road asphalt and oils	3	II/III	HGV		1											**1**
1999	Tars, Liquid, including road asphalt and oils	3	II/III	Open Bin											1		**1**
2055	Styrene monomer inhibited	3	III	Tanker							3				1		**4**
2209	Formaldehyde solution	8	III	Tanker										1			**1**
2348	Butyl Acrylate	3	III	Tanker	1					2							**3**
2381	Dimethyl Disulfide	3	II	Tanker							1						**1**
2672	Ammonia solution, with 10%<ammonia<35%	8	III	Tanker												1	**1**
2794	Batteries, Wet, Filled with acid	8	III	HGV					1			1			1	1	**4**
2794	Batteries, Wet, Filled with acid	8	III	LDV												1	**1**
2874	Furfuryl Alcohol	3.1	III	Tanker											1		**1**
3065	Alcoholic Beverages	3	II/III	ISO-tainer											1		**1**

UN No.	Dangerous Goods	Class	Danger Group	Config.	Edwin Swales VC Drive						South Coast Road						Σ
					From West			From East			From North			From South			
					WL	WS	WR	EL	ES	ER	NL	NS	NR	SL	SS	SR	
3082	Environmentally hazardous substance, liq.	9	III	Tanker	2					1	2						**5**
3092	1-Methyoxy-2-Propanol	3	III	Tanker								1					**1**
3257	Elevated temperature liquid	9	III	Container											2		**2**
3265	Corrosive liquid, acidic, organic	8	I/II/III	Container	1												**1**
	Multiload			Tanker		1		2			4	2	1	1	1		**12**
	Multiload			Container			1				1						**2**
	Multiload			HGV	1	11	2	1	4	4	6	3		5	3	1	**41**
	Multiload			LDV							2	2	1		1		**6**
Σ					**32**	**48**	**12**	**7**	**10**	**14**	**58**	**22**	**39**	**34**	**51**	**13**	**340**

B.3 M4 Southern Freeway – Duranta Road Intersection Survey

A summary of the dangerous goods surveys at the M4 Southern Freeway – Duranta Road intersection is presented in Table B.3.

Date: 8/5/2003 Times: 10:50-11:50, 13:05-14:05 Hours: 2 hours

Date: 3/7/2003 Times: 08:25-09:25, 10:25-11:25, 12:25-13:25, 14:30-15:30 Hours: 4 hours

Table B.3: Summary of dangerous goods survey at the M4 Southern Freeway – Duranta Road intersection

UN No.	Dangerous Goods	Class	Danger Group	Config.	Southern Freeway Off Ramp						Duranta Road			Σ
					From South			From North			From East			
					SL	SS	SR	NL	NS	NR	EL	ES	ER	
1075	Liquefied Petroleum Gases	2.1	-	Tanker			3						1	**4**
1075	Liquefied Petroleum Gases	2.1	-	HGV							1			**1**
1114	Benzene	3	I	Tanker							3			**3**
1202	Diesel fuel	3	III	Tanker			1				1		1	**3**
1203	Petrol	3	II	Tanker			19	25			20		32	**96**
1208	Hexanes	3	II	Tanker				1						**1**
1263	Paint related material	3	II/III	Tanker			1							**1**
1263	Paint related material	3	II/III	LDV			1							**1**
1268	Petroleum products	3	I/II/III	Tanker				2					2	**4**
1863	Aviation fuel	3	II/III	Tanker									1	**1**
1977	Nitrogen, refrigerated liquid	2.2	-	Tanker				1					1	**2**
1999	Tars, Liquid, including road asphalt and oils	3	II/III	Open Bin									1	**1**
1999	Tars, Liquid, including road asphalt and oils	3	II/III	Tanker			1	3			2		3	**9**
2448	Molten Sulphur	4.1	III	Tanker				1						**1**
2902	Methyl Isocyanate	6.1	I/II/III	Tanker			1				2			**3**
3082	Environmentally hazardous substance, liquid	9	III	Open Bin			1				2			**3**
3082	Environmentally hazardous substance, liquid	9	III	Tanker							4		1	**5**
3257	Elevated temperature liquid	9	III	Cont									1	**1**
	Multiload			LDV			2	1			3			**6**
	Multiload			HGV				1						**1**
	Multiload			Tanker							1			**1**
Σ					**0**	**0**	**30**	**35**	**0**	**0**	**39**	**0**	**44**	**148**

B.4 Tara Road – Duranta Road Intersection Survey

A summary of the dangerous goods surveys at the Tara Road – Duranta Road intersection is presented in Table B.4.

Date: 8/5/2003 Times: 09:45-10:45, 11:50-12:50 Hours: 2 hours

Date: 3/7/2003 Times: 07:25-08:25, 09:25-10:25, 11:25-12:25, 13:30-14:30 Hours: 4 hours

Table B.4: Summary of dangerous goods survey at the Tara Road – Duranta Road intersection

UN No.	Dangerous Goods	Class	Danger Group	Config.	Duranta Road						Tara Road			Byfield Road			Σ
					From West			From East			From North			From South			
					WL	WS	WR	EL	ES	ER	NL	NS	NR	SL	SS	SR	
1075	Liquefied Petroleum Gases	2.1	-	Tanker	3								5				**8**
1075	Liquefied Petroleum Gases	2.1	-	HGV									1				**1**
1105	Amyl alcohols	3	II/III	Tanker									1				**1**
1114	Benzene	3	I	Tanker	2												**2**
1193	Ethyl Methyl Ketone	3	II	Tanker	1												**1**
1202	Diesel fuel	3	III	Tanker									1				**1**
1203	Petrol	3	II	Tanker	36								47				**83**
1208	Hexanes	3	II	Tanker									1				**1**
1223	Kerosene	3	III	Tanker	2												**2**
1268	Petroleum products	3	I/II/III	Tanker	4								6				**10**
1274	n-Propanol	3	II/III	Tanker	1												**1**
1307	Xylenes	3	II/III	Tanker	1								1				**2**
1649	Tetra Ethyl Lead	6.1	I	Tanker	1												**1**
1789	Hydrochloric Acid Solution	8	II/III	Tanker	1												**1**
1824	Sodium hydroxide solution	8	II/III	Tanker													**0**

UN No.	Dangerous Goods	Class	Danger Group	Config.	Duranta Road						Tara Road			Byfield Road			Σ
					From West			From East			From North			From South			
					WL	WS	WR	EL	ES	ER	NL	NS	NR	SL	SS	SR	
1830	Sulphuric Acid with >51% acid	8	II	Tanker	1												1
1848	Propionic Acid	8	III	LDV									1				1
1863	Aviation fuel	3	II/III	Tanker	2								3				5
1978	Propane or Propane mixture	2.1	-	Tanker	2								1				3
1999	Tars, Liquid, including road asphalt and oils	3	II/III	Open Bin	4												4
1999	Tars, Liquid, including road asphalt and oils	3	II/III	Tanker	7								7				14
2448	Molten Sulphur	4.1	III	Tanker	1												1
2672	Ammonia solution, with 10%<ammonia<35%	8	III	Tanker													0
2902	Methyl Isocyanate	6.1	I/II/III	Tanker			2							2			4
3065	Alcoholic Beverages	3	II/III	Tanker													0
3082	Environmentally hazardous substance, liquid	9	III	Open Bin	4								1				5
3082	Environmentally hazardous substance, liquid.	9	III	Tanker	2		4						1	3			10
3257	Elevated temperature liquid	9	III	Tanker	1								1	1			3
	Multiload			LDV	4												4
	Multiload			Tanker	2												2
Σ					82	0	6	0	0	0	0	0	78	6	0	0	172

B.5 The Avenue East – Refinery Drive Intersection Survey

A summary of the dangerous goods surveys at The Avenue East – Refinery Drive intersection is presented in Table B.5.

Date: 7/7/2003 Times: 07:55-13:55 Hours: 6 hours

Table B.5: Summary of dangerous goods survey at The Avenue East – Refinery Drive intersection

UN No.	Dangerous Goods	Class	Danger Group	Config.	The Avenue East						Joyner Road						Σ
					From West			From East			From North			From South			
					WL	WS	WR	EL	ES	ER	NL	NS	NR	SL	SS	SR	
1075	Liquefied Petroleum Gases	2.1	-	Tanker	4		1					1	2				**8**
1075	Liquefied Petroleum Gases	2.1	-	LDV								1	1	1	1		**4**
1114	Benzene	3	I	Tanker													**0**
1123	Butyl Acetates	3	II/III	Tanker									2				**2**
1202	Diesel fuel	3	III	Tanker									2				**2**
1203	Petrol	3	II	Tanker	1								1	1			**3**
1208	Hexanes	3	II	ISO-tainer	1								1				**2**
1208	Hexanes	3	II	LDV											1		**1**
1210	Printing ink, flammable	3	II/III	Tanker													**0**
1268	Petroleum products	3	I/II/III	Tanker	4		1						6		1		**12**
1268	Petroleum products	3	I/II/III	LDV									1				**1**
1294	Toluene	3	II	Tanker	1												**1**
1300	Turpentine Substitute	3	II/III	Tanker											1		**1**
1307	Xylenes	3	II/III	Tanker	1										1		**2**
1649	Tetra Ethyl Lead	6.1	I	Tanker													**0**
1830	Sulphuric Acid with >51% acid	8	II	Tanker			1										**1**
1866	Resin Solution, flammable	3	II/III	Tanker			1								1		**2**
1866	Resin Solution, flammable	3	II/III	LDV									1		1		**2**

UN No.	Dangerous Goods	Class	Danger Group	Config.	The Avenue East						Joyner Road						Σ
					From West			From East			From North			From South			
					WL	WS	WR	EL	ES	ER	NL	NS	NR	SL	SS	SR	
1977	Nitrogen, refrigerated liquid	2.2	-	Tanker	1												**1**
1999	Tars, Liquid, including road asphalt and oils	3	II/III	Tanker	1								5		1		**7**
2055	Styrene monomer inhibited	3	III	Tanker	1								1				**2**
2214	Phthalic Anhydride	8	III	Tanker	1								2				**3**
2448	Molten Sulphur	4.1	III	Tanker	1							1					**2**
3065	Alcoholic Beverages	3	II/III	Tanker													**0**
3077	Environmentally hazardous substance, solid	8	III	Tanker	1												**1**
3092	1-Methyoxy-2-Propanol	3	III	Tanker													**0**
	Multiload			Tanker			1							1			**2**
	Multiload			LDV	4	1	4		2	1		3	5	3	1		**24**
	Multiload			HGV									1				**1**
	Unmarked			Tanker	2												**2**
Σ					**24**	**1**	**9**	**0**	**2**	**1**	**0**	**6**	**31**	**6**	**9**	**0**	**89**

C. APPENDIX C: Estimation of Annual Traffic Volume

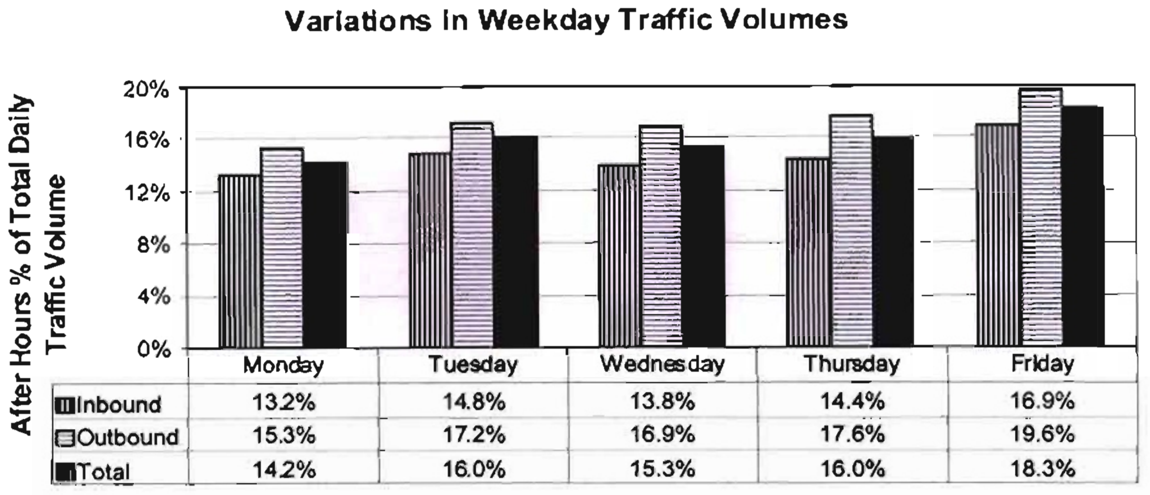
The eThekwini Municipality conducts manual counts of traffic volumes at intersections within the metropolitan area. Twelve-hour counts of traffic volumes are undertaken, usually between 6 a.m. and 6 p.m. on a weekday. Twenty-four-hour, seven-day traffic volumes were not available for the Edwin Swales VC Drive – South Coast Road intersection, or for any of the other four intersections surveyed in this investigation.

Twenty-four-hour, seven-day traffic volumes were obtained for a location within the Durban South Basin, in reasonably close proximity to the selected intersections. This data was analysed and the following procedure was developed to expand the twelve-hour eThekwini Municipality intersection traffic volume count into an *Annual Traffic Volume*, taking into consideration after-hours and weekend traffic.

C.1 Expansion of Twelve-Hour Count into Total Weekday Traffic Volume

The only complete data set available from the eThekwini Municipality Transport Authority were traffic volumes taken on the M4 Southern Freeway between Duranta Road and Himalayas Road from 00:00:00 on Wednesday 24 April 2002 until 24:00:00 on Tuesday 30 April 2002. Data for all six lanes of the M4 Southern Freeway (both inbound and outbound carriageways) were available. Unfortunately, traffic volumes disaggregated by vehicle type were not available.

The M4 Southern Freeway traffic volumes were analysed for each weekday in order to calculate the *After-hours percentage of total weekday traffic*, i.e. the proportion of the total weekday count recorded between midnight and 6 a.m., and between 6 p.m. and 12 p.m. Figure C.1 illustrates the variation in percentage of total daily traffic recorded after-hours on weekdays. Note that the days of the week have been rearranged from the date order.



	Monday	Tuesday	Wednesday	Thursday	Friday
Inbound	13.2%	14.8%	13.8%	14.4%	16.9%
Outbound	15.3%	17.2%	16.9%	17.6%	19.6%
Total	14.2%	16.0%	15.3%	16.0%	18.3%

Figure C.1: After-hours percentage of total daily traffic volume, M4 Southern Freeway

On average, 16 per-cent of the total weekday traffic volume on the M4 Southern Freeway was recorded between midnight and 6 a.m., and between 6 p.m. and 12 p.m. Let δ be the percentage of the total weekday traffic volume recorded after-hours. Then:

$$\textit{After hours traffic volume} = \delta \times \textit{Total Weekday traffic volume} \tag{C.1}$$

$$\begin{aligned} &\textit{Total Weekday traffic volume} \\ &= (\textit{6 a.m. to 6 p.m. traffic volume}) + (\textit{After hours traffic volume}) \quad \text{(C.2)} \\ &= (\textit{6 a.m. to 6 p.m. traffic volume}) + (\delta \times \textit{Total Weekday traffic volume}) \end{aligned}$$

Simplifying Equations (C.1) and (C.2), yields the formula for the total weekday traffic volume:

$$\textit{Total Weekday traffic volume} = \frac{(\textit{6 a.m. to 6 p.m. traffic volume})}{1-\delta} \tag{C.3}$$

A total volume of 8985 heavy vehicles entered the Edwin Swales VC Drive – South Coast Road intersection between 6 a.m. and 6 p.m. during the eThekwini Municipality traffic count on 22 April 2002. As this traffic count was conducted relatively recently, no steps were taken to adjust this volume to allow for growth over time.

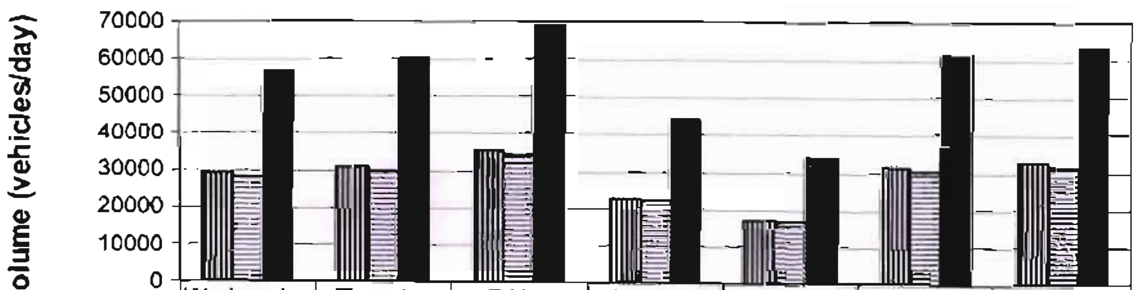
The assumption was made that the M4 Southern Freeway traffic volumes for all vehicle types, are indicative of after-hours and weekend heavy-vehicle traffic within the Durban South Basin, as no other data are available. Hence, at the Edwin Swales VC Drive – South Coast Road intersection, the total heavy-vehicle weekday traffic volume may be estimated as:

$$\begin{aligned}
&\textit{Total Heavy-vehicle Weekday traffic volume}\\
&= \frac{\textit{Twelve-hour eThekwini Municipality traffic volume}}{\textit{1 - After hours percentage of total daily traffic volume}}\\
&= \frac{\textit{8985 Heavy vehicles}}{1 - 0.16} = 1.19 \times 8985\\
&= \textit{10692 Entering Heavy vehicles/Weekday}
\end{aligned} \tag{C.4}$$

C.2 Expansion of Total Weekday Traffic Volume into Annual Traffic Volume

The M4 Southern Freeway traffic volumes were also analysed to calculate the contribution of *weekend* traffic volumes to the total *weekly* traffic volume. Figure C.2 illustrates the daily variations in traffic volume.

Daily Variations in Traffic Volume



	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday
Inbound	28950	30701	35101	22471	17268	31144	32281
Outbound	27821	29682	34116	21925	16516	30057	31350
Total	56771	60383	69217	44396	33784	61201	63631

Figure C.2: Daily variations in traffic volume, M4 Southern Freeway

On average, 20 per-cent of the total weekly traffic volume on the M4 Southern Freeway was recorded on Saturday and Sunday, i.e. on weekends or *non-weekdays*. Let β be the percentage of the total weekly traffic volume recorded on weekends. Then:

$$\textit{Weekend traffic volume} = \beta \times \textit{Total weekly traffic volume} \tag{C.5}$$

$$\begin{aligned}
&\textit{Total weekly traffic volume}\\
&= (5 \times \textit{Total Weekday traffic volume}) + \textit{Weekend traffic volume}\\
&= (5 \times \textit{Total Weekday traffic volume}) + (\beta \times \textit{Total weekly traffic volume})
\end{aligned} \tag{C.6}$$

Simplifying Equations (C.5) and (C.6), yields the formula for the total weekly traffic volume:

$$\textit{Total weekly traffic volume} = \frac{5 \times \textit{Total Weekday traffic volume}}{1-\beta} \tag{C.7}$$

Substituting into Equation (C.5), yields:

$$\textit{Weekend traffic volume} = \frac{\beta \times 5 \times \textit{Total Weekday traffic volume}}{1-\beta} \tag{C.8}$$

Hence, the *non-weekday* traffic volume may be estimated as:

$$\begin{aligned}
&\textit{Non-weekday traffic volume} = \frac{\textit{Weekend traffic volume}}{2}\\
&= \frac{\beta \times 5 \times \textit{Total Weekday traffic volume}}{2 \times (1-\beta)}\\
&= \frac{2.5 \times \beta \times \textit{Total Weekday traffic volume}}{1-\beta}
\end{aligned} \tag{C.9}$$

South Africa has twelve public holidays. Hence, there are essentially 116 *non-weekdays* per year (i.e. 12 public holidays + [52 weekends x 2 days per weekend]). Thus, the annual traffic volume may be separated into 249 days of normal weekday traffic volumes and 116 days of *non-weekday* traffic volumes per year (assuming no public holidays fall on a Sunday). Hence, the annual traffic volume may be estimated as:

$$\begin{aligned}&\textit{Annual traffic volume}\\&=\left(249\times \textit{Total Weekday traffic volume}\right)\\&+\left(116\times \textit{Non-weekday traffic volume}\right)\end{aligned} \qquad \text{(C.10)}$$

Substituting into Equation (C.9), yields:

$$\begin{aligned}&\textit{Annual traffic volume}\\&=\left(249\times \textit{Total Weekday traffic volume}\right)\\&+\left(116\times\left[\frac{2.5\times\beta\times \textit{Total Weekday traffic volume}}{1\text{-}\beta}\right]\right)\\&=\textit{Total Weekday traffic volume}\times\left\{249+\left(\frac{290\times\beta}{1\text{-}\beta}\right)\right\}\end{aligned} \qquad \text{(C.11)}$$

Hence, at the Edwin Swales VC Drive – South Coast Road intersection, the annual traffic volume may be estimated as:

$$\begin{aligned}&\textit{Annual traffic volume}\\&=\textit{Total Weekday traffic volume}\times\left\{249+\left(\frac{290\times\beta}{1\text{-}\beta}\right)\right\}\\&=10692\ \textit{Heavy vehicles/Weekday}\times\left\{249+\left(\frac{290\times 0.20}{1-0.20}\right)\right\}\\&=3.44\times 10^{6}\ \textit{Entering Heavy vehicles/year}\end{aligned} \qquad \text{(C.12)}$$

There may be serious limitations in extrapolating the *Annual Traffic Volume* using the procedure described in this appendix. Fortunately, as discussed in Section 4.1.9, the specific manner in which the model for estimating the *Dangerous Goods Accident Rate* and the *Dangerous Goods Releasing Accident Rate* has been formulated, resulted in the *Exposure* term (measured in units of Entering Heavy vehicles/year) being "cancelled out". However, if there are no heavy vehicles entering the intersection, there will be no heavy-vehicle accidents. Thus, *Exposure* and *Accident Rate* are clearly not independent of each other.

D. APPENDIX D: Estimation of Emission Rate from Evaporating Pools

Kawamura & Mackay [1985] developed the following relationships to estimate the emission rate for dangerous goods releases that form evaporating pools:

$$E = \frac{A \times K_m \times MW \times P_v}{R \times T} \ (kg/s) \qquad \text{(D.1)}$$

where:

E = evaporation rate [kg/s]

A = area of the evaporating pool [m^2]

K_m = mass transfer coefficient [m/s]

MW = molecular weight of the selected chemical [kg/kmol]

P_v = vapour pressure of the selected chemical [Pa]

R = the gas constant (8314 J/(kmol.K))

T = ambient temperature [K]

The mass transfer coefficient K_m, is estimated as:

$$K_m = 0.0048 \times U^{7/9} \times Z^{-1/9} \times Sc^{-2/3} \ (m/s) \qquad \text{(D.2)}$$

where:

U = wind speed at a height of 10 m [m/s]

Z = the pool diameter in the along-wind direction [m]

Sc = the laminar Schmidt number for the selected chemical (a dimensionless ratio)

The Schmidt number, which is a unitless ratio, is estimated as:

$$Sc = \frac{v}{D_m} \qquad \text{(D.3)}$$

where:

v = the kinematic viscosity of air, assumed to be 1.5×10^{-5} m^2/s

D_m = the molecular diffusivity of the selected chemical in air [m^2/s]

Graham's Law is used to estimate the molecular diffusivity of the selected chemical in air:

$$D_m = D_{H2O} \times \sqrt{\frac{MW_{H2O}}{MW_{chem}}} \ (m^2/s) \tag{D.4}$$

where:

D_{H2O} = the molecular diffusivity of water (2.4 x 10^{-5} m^2/s at 8°C)

MW_{H2O} = the molecular weight of water (18 kg/kmol)

MW_{chem} = the molecular weight of the selected chemical [kg/kmol]

Combining terms and simplifying yields *E*, the evaporation rate:

$$E = \frac{0.0172 \times A \times U^{7/9} \times Z^{-1/9} \times MW^{2/3} \times P_v}{R \times T} \ (kg/s) \tag{D.5}$$

where:

E = evaporation rate [kg/s]

A = area of the evaporating pool [m^2]

U = wind speed at a height of 10 m [m/s]

Z = the pool diameter in the along-wind direction [m]

MW = molecular weight of the selected chemical [kg/kmol]

P_v = vapour pressure of the selected chemical [Pa]

R = the gas constant (8314 J/(kmol.K))

T = ambient temperature [K [Kawamura & Mackay, 1985]

Table D.1 provides relevant chemical properties for use with Equation (D.5) when estimating evaporation rates for the selected dangerous goods under investigation.

Table D.1: Relevant chemical properties for selected chemicals [NIOSH, 2002]

Dangerous Goods	**Vapour Pressure @ 20 °C** [Pa]	**Molecular Weight** [kg/kmol]
Anhydrous Hydrogen Fluoride	103000	20.006
Acrylonitrile	11066	53.064
Benzene	9999	78.114
Isopropylamine	61328	59.112
Tetra Ethyl Lead	27	323.45
Methyl Isocyanate	46396	57.052

E. APPENDIX E: Passive Methyl Isocyanate Release

E.1 Methyl Isocyanate Release at the Tara Road – Duranta Road Intersection

As discussed in Section 3.4.4, due to incorrect use of signage by the hauliers, there is some concern as to whether Methyl Isocyanate is actually being transported through the M4 Southern Freeway – Duranta Road and Tara Road – Duranta Road intersections. Nevertheless, graphical risk profiles for a Methyl Isocyanate release at the Tara Road – Duranta Road intersection are presented in this appendix.

Figure E.1 presents isopleths indicating the downwind distances to the exposure limits: IDLH and ERPG-3 for a Methyl Isocyanate release (1 kg/s emission rate) at the Tara Road – Duranta Road intersection.

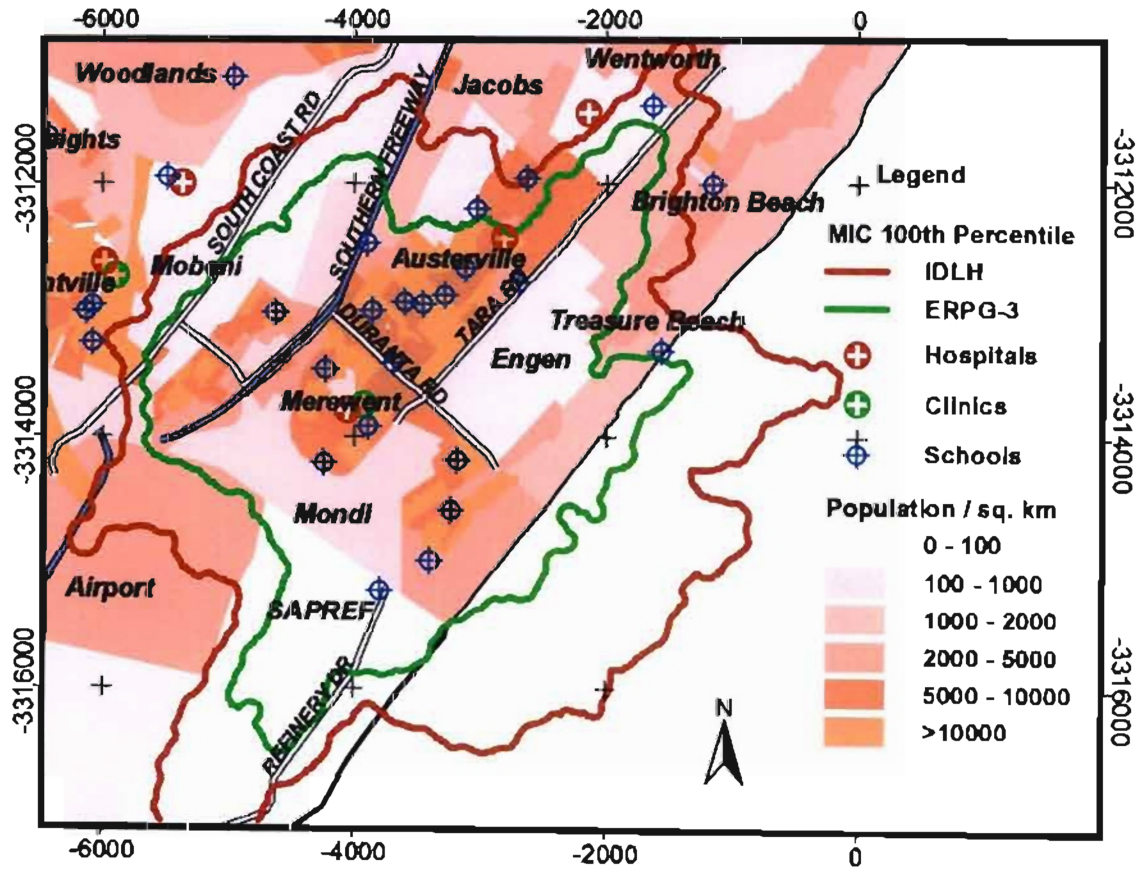


Figure E.1: The extent of the impact on the area surrounding the Tara Road – Duranta Road intersection of ground level concentrations following a Methyl Isocyanate (MIC) release (1 kg/s emission rate), using the ERPG and IDLH guidelines

Methyl Isocyanate has a low ERPG-3 concentration of 5 ppm [NIOSH, 2002]. Figure E.1 indicates that concentrations of Methyl Isocyanate above the ERPG-3 level may exist as far out as 3.2 kilometres from the intersection. The ERPG-3 isopleth in Figure E.1 covers an area of 12.7 km^2. The residential population density is relatively high in the area surrounding the Tara Road – Duranta Road intersection. Approximately 45000 residents within the ERPG-3 isopleth are potentially at risk, and if exposed would be expected to experience or develop life-threatening health effects. Depending on the direction the wind is blowing towards, in the event of a large Methyl Isocyanate release at the Tara Road – Duranta Road intersection, it is recommended that the affected parts of the Austerville, Merewent, Wentworth, Brighton Beach and Treasure Beach residential areas; the affected parts of the Mobeni industrial area, the Durban International Airport, Mondi, the Engen and SAPREF oil refineries; and the affected schools, hospitals and clinics within the ERPG-3 isopleth be evacuated until the spill has been contained and removed. The ERPG-2 isopleth was not plotted as it extends beyond the receptor grid chosen in ADMS™. The *Emergency Response Guidebook* [2004] recommends a Protective Action Distance of 8.7 kilometres during the day and "11+" kilometres at night for a "large" Methyl Isocyanate spill. Depending on the wind direction, occupants of vehicles travelling on the M4 Southern Freeway may be exposed to high concentrations of Methyl Isocyanate for short periods of time as they travel through and along the dispersing plume.

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