國立交通大學

工學院產業安全與防災碩士在職專班

碩士論文

以六個標準差，評析危險品運輸的環境及社會風險

SIX SIGMA AND ENVIRONMENTAL AND SOCIETAL RISK ASSESSMENT FOR DANGEROUS GOODS TRANSPORT

研 究 生： 鄭允豪

指導教授： 陳俊勳 教授

于樹偉 教授

中 華 民 國 九十八年 二 月

以六個標準差，評析危險品運輸的環境及社會風險

SIX SIGMA AND ENVIRONMENTAL AND SOCIETAL RISK ASSESSMENT FOR DANGEROUS GOOD TRANSPORT

研究生：鄭允豪　Student：Yun-Hao Cheng

指導教授：陳俊勳　教授　Advisor：Chiun Hsun Chen

于樹偉　教授　Advisor：Shuh Woei Yu

國立交通大學

工學院產業安全與防災碩士在職專班

碩士論文

A Thesis

Submitted to the Department of Industrial Safety and Risk Management

College of Engineering

National Chiao Tung University

in Partial Fulfillment of the Requirements

for the Degree of

Master

in

Industrial Safety and Risk Management

Hsinchu, Taiwan, Republic of China

February 2009

中文摘要

由於其動態的特性，危險品運輸的風險比生產工廠的風險要來得高，而因為運輸的意外事件所造成的後果，及其對環境以及人的影響，尤其是對人口較為密集地區的影響，是難以估計的。因此，很多國家要求應用量化風險評估的方法及管理系統確保危險品運輸的安全。危險品運輸的風險管理是一個非常複雜的流程，它包含了危害鑑別、風險評估及控制、監控、控制機制的維持、意外事件的呈報及緊急應變等。

有效率的危險品運輸風險評估，涉及非常廣泛的資訊，如危險品本身的危害、氣象條件、交通狀況、車輛安全規範、危險品的包裝、運輸路線、運輸路線人口密度等等。本論文嘗試以液氯槽車運輸為例，並應用相關分析方法進行事故情境假定、背景資訊管理、量化社會風險評估、以及六個標準差統計方法之應用。依據風險評估流程及結果的品質，六個標準差的方法確實扮演了一個成功的重要元素之一。相信本論文所揭露的方法，應做為其他相關危險品運輸的環境風險評估之參考。

關鍵詞: 1. 危險品運輸 2. 量化風險評估 3. 六個標準差.

Abstract

Because of its dynamic nature, transport of dangerous goods poses greater risk than fixed-location manufacturing facilities. The consequences of incidents and their impact on the environment and the general public, especially in highly populated areas, are very difficult to estimate. Therefore, it is mandatory to apply quantitative risk assessment and management systems to ensure the safety of dangerous goods transport in many countries. Transport risk management is a very complex process, consisting of various tasks for hazard identification, risk assessment and control, monitoring and maintaining of the control mechanism, incident reporting and emergency response.

An effective risk assessment of the transport of dangerous goods involves a wide range of information, such as inherent hazards of the materials, meteorological conditions, traffic characteristics, vehicle safety specifications, packaging of the goods, route selection, and population distribution along the route, etc. This thesis uses chlorine transport as an example and to outline the methodologies applied in scenario development, background information management, quantitative societal risk assessment, and the application of Six Sigma principles. Based on the results of both the assessment processes and the final results, it is clear that Six Sigma provides a key factor to the success of this study. It is believed that the methodologies outlined in this thesis can be extended to environmental risk assessment and other operations of the transport of dangerous goods.

Key words: 1. dangerous goods transport 2. quantitative risk assessment 3. Six Sigma.

誌謝

非常感謝家人在學生在職進修期間，無怨無悔的付出，更感謝指導教授陳俊勳教授、于樹偉教授、高振山教授，以及公司長官馮廷權協理不厭其煩的諄諄教誨。僅將此研究成果及喜悅與他們共享。

Table of Contents

Chapter 1 Introduction

Chapter 2 Theory for Quantitative Risk Assessment and Six Sigma

Chapter 3 Methodology

Chapter 4 Results and Discussions

List of Tables

List of Figures

Chapter 1 Introduction

1.1 Motivation

Hazardous materials transport is highly heterogeneous and complex. It involves all players in the supply chain, such as manufacturers, shippers, carriers, container providers, and receivers. Because of the potential impacts of accidental releases, emergency responders, regulators, and the general public have to be taken into consideration as well. The communities along the transport route and road users are involuntary players. The thesis selected liquid chlorine highway transport as case study. Key reason is that liquid chlorine transport is relatively risky comparing to other dangerous good transport.

Chlorine is a greenish-yellow colored gas at ambient conditions. It is approximately 2.5 times heavier than air and tends to displace air at low elevations. Chlorine is normally stored and transported as a liquefied compressed gas.

Since ambient pressure is lower than the storage pressure, any release of liquefied compressed gas will expand and partially vaporize or flash. Small chlorine liquid droplets will be formed in this vapor and liquid mixture. Some of the droplets may fall to the ground and begin to form a pool of cold liquid chlorine at -36^0C. This pool will rapidly evaporate as it is heated by the substrate and surrounding air.

The remainders of the droplets and the flashed vapors form aerosols, which begin to move in the direction of the prevailing wind. Due to the density of chlorine gas, the tendency of the vapor cloud will be spread in the direction perpendicular to the wind direction. During this process, air will be entrained into the vapor cloud and reduce the chlorine concentration in the air. The cloud will no longer poses danger when sufficient quantities of air are mixed into the cloud at some distance downstream from the release point.

Even in small amount, chlorine can cause severe irritation to the mucous membranes of the eyes, nose, throat, and the entire respiratory tract. Chlorine affects humans by reacting with water in human tissue. The chlorine strong oxidizing capacity splits hydrogen from water in the moist tissue producing nascent oxygen and hydrochloric acid. The oxygen causes irritation which is enhanced by the hydrochloric acid. This irritation can lead to major tissue damage with sufficient inhalation.

Chlorine has an irritating, bleach-like odor that can be detected by smell at very low airborne concentrations of around 0.2 to 0.4 ppm. At a concentration of 1ppm, irritation of the eyes, noise and throat starts to occur. Problems with breathing in humans can begin to occur as low as 15 ppm. At 40 to 60 ppm, airborne chlorine is dangerous for a 30 minute exposure. A 100ppm concentration for a 10 minute exposure may lead to fatalities in vulnerable groups. A concentration in excess of 1,000 ppm lethal after only a few deep breaths.

The exposure guides for chlorine include

1. Odor threshold for most people is around 0.3 ppm.

2. The AEL (Acceptable Exposure Limit) established by DuPont Haskell Lab, in any 8-hour work shift of a 40-hour workweek shall not exceed 0.5 ppm. Higher levels require respiratory protections.
3. CEG (Community Exposure Guide) is 0.05 ppm maximum for a 24-hour period.
4. The OSHA Permissible Exposure Level (PEL) is 1 ppm ceiling.
5. The immediately Dangerous to Life and Health Level (IDLH) is 25 ppm.
6. The Extreme Exposure Level is 1 minute for 10 ppm, 1-5 minutes for 7 ppm and 5-60 minutes for 5 ppm.
7. Emergency Response Planning Guide, ERPG level 1 is 1 ppm, level 2 is 3 ppm, and level 3 is 20 ppm.

Liquefied chlorine has been transported by road and rail for over 80 years. Numerous evaluations of chlorine transport safety have been done by industry and government agencies. Industry in general has implemented many safeguards to prevent accidental releases and to mitigate the effects of any releases. This effort has resulted in the current widely employed practices involved with shipping chlorine by road and rail. In spite of these efforts, there have been accidents.

Herewith several severe chlorine transport accidents happened in the past several decades. The most severe incident to-date occurred at an urban railway station in San Luis Potosi, Mexico on 31 July, 1981. Due to an air brake failure on the locomotive, a series of more than 28 railcars derailed and overturned, releasing approximately 300 tones of chlorine. There were 14-20 fatalities associated with this accident and 280 people affected. On 26 February, 1978, a rail car derailment in Youngstown Florida, USA led to a release of chlorine gas resulting in eight fatalities. The cause of this accident was attributed to sabotage. On 19 September, 1985, a rail car leaked chlorine into a crowded urban area in Fushun, Mainland China and forced approximately 2,000 people to seek medical help. It is unknown how many fatalities were resulted. On 31 January, 1961, a derailed tank car spilled approximately 6,000 gallons of chlorine near La barre, Louisiana. The vapor cloud spread over an area of approximately 4 square kilometers. A concentration of 10 ppm was measured approximately 1,800 meters away from the release point. While a single fatality resulted from this vent, several survived by remaining indoors where the chlorine concentration remained lower than outdoors. On August 14, 2002, a chlorine transfer hose ruptured during a rail car unloading operation at the DPC Enterprises chlorine repackaging facility near Festus, Missouri. The hose rupture ultimately led to the release of 48,000 pounds of chlorine, causing three workers and 63 residents to seek medical treatment. On November 17, 2003, there was a release of chlorine gas from the DPC Enterprises chlorine repackaging facility in Glendale, Arizona, near Phoenix. Fourteen people, including ten police officers, required treatment for chlorine exposure. The release occurred when chlorine vapors from a rail car unloading operation escaped from a system designed to recapture the material, known as a scrubber. Owing to the exhaustion of absorbent chemicals in the scrubber, chlorine gas was released. On June 28, 2004, one chlorine rail car punctured at one end of a rail flat car and the trailing end of the flat car was buckled inwards in Texarkana, Arkansas resulted in 3 fatalities. One March 29, 2005, one overloaded chlorine trailer punctured at one end of another truck and then rollover at Jiangsu highway, China. Tones of chlorine was released to the atmosphere and resulted in over 25 fatalities and hundreds of people were hospitalized.

1.2 Literature Review

Borysiewicz [1] abstracted the framework of transport risk assessment in his thesis of “Transport Risk Assessment” which includes the following process steps:

1. Incident enumeration
2. Selection
3. Consequence estimation
4. Likelihood estimation
5. Risk estimation
6. Utilization of risk estimates

Knoflacher, et al [2], highlighted that risk is defined by two aspects: the occurrence probability of an event and the consequences of an occurring event. A common way to describe societal risk is to calculate F-N curves, which F-N curves illustrate the relationship between accident frequency and accident severity. On the abscissa the number of victims x (fatalities, injured people or both) is shown in logarithmic scale. On the ordinate the corresponding yearly frequencies F(x) for the occurrence of accidents with x victims are shown (also in logarithmic scale). For each given situation (population, traffic, dangerous good traffic, route, weather, etc.) one F-N curve represents the societal risk. The following figure gives as an example for an F-N curve.

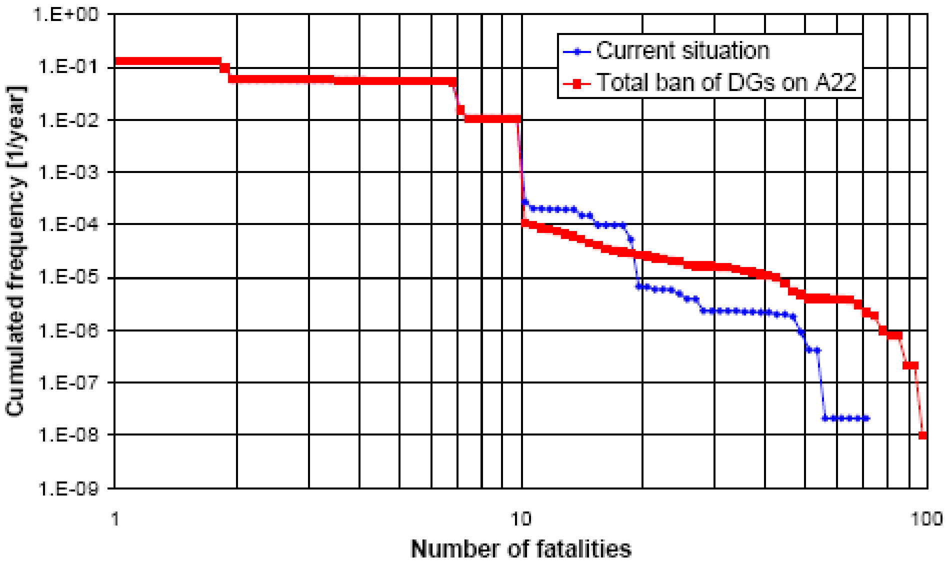


Figure 1.1 F-N curve, cumulated frequency versus number of fatalities

Source: H. Knoflacher, P. C. Pfaffenbichler, H. Nussbaumer, Quantitative Risk Assessment of Heavy Goods Vehicle Transport through Tunnels – the Tauerntunnel Case Study, pp 2-3.

A complete assessment of risks caused by transport of dangerous goods would require the consideration of all kinds of dangerous materials, all meteorological conditions, all accidents, sizes of breaches, vehicles fully or partially loaded, etc. The coverage of all circumstances is impossible, so simplifications have to be made. The QRA model developed by OECD (Organization of Economic Co-operation and Development) is based on the following steps:

1. Choose a relative small but representative number of goods;
2. Select a relative small but representative number of accident scenarios involving these goods;
3. Determine the physical effects of these scenarios (for open road and tunnel sections);
4. Determine the physiological effects of these scenarios on road users and local population (fatalities and injuries);
5. Take into account the chance to escape and/or shelter
6. Take into account different risk reduction measures and
7. Determine the associated probabilities of occurrence.

Hamouda [3], highlighted that Quantitative Risk Assessment (QRA) methods are commonly used to assess HazMat risk during transport. A QRA consists of identifying the accidental events and combining the expected frequencies and consequences to obtain a proper risk measure while taking into account both the likelihood and the magnitude of the hazard. The following three-stage framework for risk analysis in transport was recommended:

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

CCPS, Center for Chemical Process Safety [4], has detailed descriptions of measurement, calculation, and presentation of risk estimates at chapter 4 of its publication of “Guidelines for Chemical Process Quantitative Risk Assessment” as shown below:

1. Risk indices are single numbers or tabulations of numbers which are correlated to the magnitude of risk. Some risk indices are relative with no specific units, which only have meaning within the context of the risk index calculation methodology. Other risk indices are calculated from various individual or societal risk data sets and represent a condensation of the information contained in the corresponding data set. Risk indices are easy to explain and present, but contain less information than other, more complex measures.
2. Individual risk measures can be single numbers or a set of risk estimates for various individuals or geographic locations. In general, they consider the risk to an individual who

may be in the effect zone of an incident or set of incidents. The size of the incident, in terms of the number of people impacted by a single event, does not affect individual risk. Individual risk measures can be single numbers, table of numbers, or various graphical summaries.

3. Societal risk measures are single number measures, tabular sets of numbers, or graphical summaries which estimate risk to a group of people located in the effect zone. Societal risk estimates include a measure of incident size (for example, in terms of the number of people impacted by the incident of set of incidents considered). Some societal risk measures are designed to reflect the observation that people tend to be more concerned about the risk of large incidents than small incidents, and may place a greater weight on large incidents.

Monnier and Gheorghe [5] highlighted the data needed for estimating the consequences of hazardous material transport in the thesis of "Quantitative Risk Assessment of Hazardous Materials Transport Systems" which should include the following data:

1. The nature of materials being transported
2. The storage/transport conditions(temperature, pressure, etc)
3. The quantity of the load
4. The nature of the transport tanker(s) including configuration of major characteristics.
5. Prevailing meteorological conditions applicable to the road network under consideration (including wind speed, direction and where possible atmospheric stability)
6. Topographical characteristics of the general area-both natural and man-made.
7. Land use survey of the surrounding areas along the transport route, including the type and nature of land use (residential, commercial, schools, hospitals, etc) and the residential/population density associated with each type of land use.

Rhyne [6] highlighted the quantitative risk analysis process at his "Hazardous Materials Transport Risk Analysis – Quantitative Approaches for Truck and Train", and the process shall include the following steps:

1. Preliminary hazards analysis: define objectives, scope, and level of effort, identify hazards, determine consequences of interest, and identify initiating events.
2. Accident scenario development: identify accident forces, and evaluate failure modes.
3. Frequency analysis: evaluate initiator frequency, estimate conditional probability of a release, and determine conditional probabilities for consequence analysis
4. Consequence analysis: characterize source term, quantify exposure and effect, and estimate population exposed.
5. Risk evaluation: estimate risks, identify major contributors, define/evaluate risk reduction alternatives, and document analysis.

Harry [7] highlighted the Six Sigma breakthrough strategy in his publishing of "The Vision of Six Sigma: Tools and Methods for Breakthrough", which includes

1. Select CTQ Characteristics
2. Define Performance Standards
3. Validate Measurement System
4. Establish Product Capability
5. Define Performance Objectives
6. Identify Variation Sources
7. Screen Potential Causes
8. Discover Variable Relationships
9. Establish Operating Tolerances
10. Validate Measurement System
11. Determine Process Capability
12. Implement Process Controls

In this thesis, liquid chlorine is transported in bulk tank trucks from the production facility, located in southern Taiwan, to Company A’s plant in the north. The route is comprised of approximately 350 kilometers of expressway and local roads. Drivers of the tank trucks are employed by Company C, a subcontractor to Company B. Both Companies A and B conduct background checks for new drivers prior to employment, and have the right to reject applicants. Background checks include medical and driving records. These checks are intended to screen out the drivers who have a history of drug or alcohol abuses, general medical problems, or limited driving experience.

Chlorine is a highly toxic gas at ambient conditions and has the potential to cause severe pulmonary irritation, pulmonary edema, and even death. A crucial aspect of the transport of hazardous chemicals is the potential risks associated with accidental releases. The formation of a toxic vapor cloud poses great threat to the environment and the surrounding population of the accident site. Therefore, acute toxicity risks of liquid chlorine transport must be carefully evaluated and managed.

Company A’s risk management policy dictates an evaluation of the risk associated with transporting chlorine from Company B, the producer of chlorine, to its plant every five years. In addition to transport, risks associated with loading, unloading and storage has to be assessed as well. For illustration purposes, the process and steps for societal risk assessment are presented in this thesis.

1.3 Scope of Present Study

Several objectives of this assessment are expected, which include

1. Provide understanding of factors influencing the acute risks to the public associated with the transport operations as conducted currently.
2. Assess quantitative risks from accident-related puncture scenarios for selected route segments (base case).
3. Evaluate qualitatively and quantitatively the impact of risk reduction options already

identified and in the process of being implemented (mitigated case), for example:

  (1) Improved driver performance, equipment maintenance, etc. resulting in reduced accident frequency
  (2) Improved tanker design, inspections, etc. resulting in reduced conditional release probability

4. Consider the need for further risk reduction.

(1) Comparison to established standard(s) for societal and individual risk as well as to background risks experienced by the Taiwan public.

(2) Identify and evaluate qualitatively and quantitatively the potential impact of other risk reduction options (mitigated case), for example:

   1. Reduced accident rates or consequences due to routing modifications.
   2. Reduced accident rate due to fewer trips by using larger capacity trailer.
   3. Reduced consequences due to improved emergency response.
   4. Provide recommendations for managing risks, both short and long term.

The process steps for applying Six Sigma Methodology will be “define”, “measure”, “analyze”, “improve”, and “control”. More introductions on Six Sigma methodology will be illustrated in Section 2.5 of Chapter 2 and Section 4.2 of Chapter 4.

Chapter 2 Theory for Quantitative Risk Assessment and Six Sigma

This chapter outlines the six sigma and quantitative risk assessment theories applied to this study. It also describes the concepts of the individual risk and societal concepts used in this study.

2.1 Risk Acceptable Criteria-the ALARP Principle

Quantitative risk assessment, QRA, provides a numerical measure of risk by combining the frequency of all events which could pose adverse impact on people and the environment with the consequential effects of all such events. QRA facilitates the planning and engineering decisions based on understanding of the major risk contributors, and helps to evaluate whether the proposed mitigating measures are effective in reducing the risk.

Since it uses physical and statistical models to predict both the likelihood and consequences of credible scenarios, QRA has the ability to account for numerous factors which influence the risk estimation. The following is a partial list of factors which QRA can utilize to estimate the risk.

The concept of so-called as low as reasonably practicable (ALARP) is the major innovation in risk management of hazardous industries. The ALARP principle is a fundamental to the regulation of health and safety in the UK and extensively used in USA and Norway. This concept requires that risks should be weighed against the costs of reducing them. Measures must be taken to reduce or eliminate the risks unless the cost of doing so is obviously unreasonable compared with the risk. The ALARP approach requires that risk between both highest and lowest limit levels must be reduced to a reasonable level in which forward risk reduction is not practicable or its cost is disproportionate to the improvement gained, see the following figure for the Risk limit level and ALARP concept.

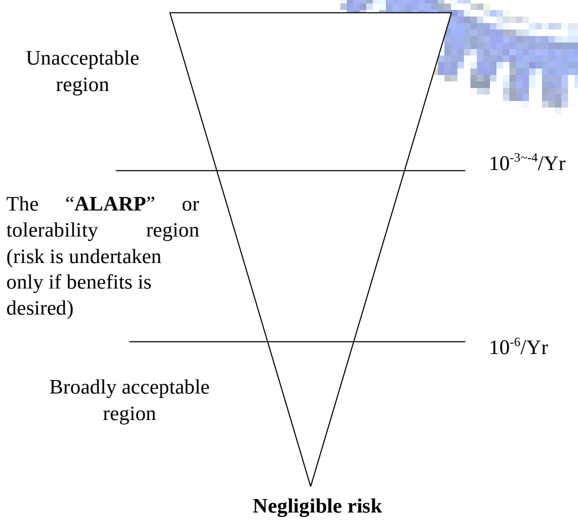


Figure 2.1 Risk limit level and ALARP concept (Source: HSE: The tolerability of risk from nuclear power stations. London: Health and Safety Executive, 1992)

2.2 Risk Summation

Considerable amount of data is generated in the frequency and consequence analyses. For each release scenario the frequency and the consequence of a given outcome must be combined. A summation procedure is adopted in order to present the risk results in a manageable format. Risk is commonly presented in two different formats: individual risk, and societal (or group) risk.

2.3 Individual Risk

Individual risk is defined as the frequency at which an individual is expected to sustain a given level of harm from the realization of specified hazards. It is usually expressed as the risk of death, and as a risk per year. Individual risk contours provide an estimate of the chance of fatality per year for a person continuously located at a given position. For example, a 10^{-6} risk location indicates a 1 in 1,000,000 chance per year of fatality.

Since any given individual along a transport route is exposed to risk for only a short period of time when the accident involves a passing truck, individual risk represented by the likelihood of fatality on an annual basis is not desirable as a primary result.

2.4 Societal Risk

Individual risk only provides an indication of the risk to a single person being a fatality, rather than any person. A large number of people exposed to relatively small levels of risk may result in a large societal (or group) risk. Societal risk is a combination of individual risk levels with an estimate of the population at risk. Societal risk is often expressed as an F-N curve, showing the cumulative frequency (F) of accidents involving N or more fatalities.

The F-N curve provides a measure of how the total risk is distributed between small, medium, and large accidental releases. This measure is a legitimate factor when judging safety, since people have an aversion against accidents with multiple fatalities. Risk reduction measures can be easily evaluated by drawing an “existing” and “mitigated” F-N curve together. F-N curves are the primary means of presenting societal risk results in this study and are also used to address risk tolerability.

This case study involved not just the chlorine manufacturer, the consumer and the transport company, outside consulting companies were also hired to provide essential expertise in areas such as past incident analysis, compilation and analysis of population data and meteorological data. Because of the complex scope of this project, integrating the fundamental principles of Six Sigma was deemed necessary by Company A in the initial stage of the project. Critical steps and results of chlorine transport risk assessment and the functions of Six Sigma are described below.

2.5 The Six Sigma Principles Used in this Study

The Six Sigma is a formal and disciplined methodology for defining, measuring, analyzing, improving and control processes. The philosophy of Six Sigma is to continuously reduce variation in processes and aims at the elimination of defects or failures from every product, service and activity. The Six Sigma can be defined both in statistical and business terms. In business terms, Six Sigma is a business improvement strategy used to improve profitability, to reduce waste, to reduce quality costs and to improve the efficiency and effectiveness of operations that meet or exceed customers' needs. In statistical terms, Six Sigma means 3.4 defects per million opportunities.

The key to the success of the Six Sigma program is the step-wise approach using "define", "measure", "analyze", "improve", and "control" (DMAIC) methodology. The definition phase entails the definition of the problem and the definition of critical quality characteristics which are most important to customers. In the measure phase, select the most appropriate output quality characteristics to be improved and establish what is unacceptable performance or a defect for such characteristics.

The next step is to gather preliminary data to evaluate current process performance and capability. In the analysis phase, one needs to analyze the root causes of defects or errors. In the improvement phase, reduction of the defect rate or number of defects is the key function using simple yet powerful statistical techniques.

There are many challenges in project management such as data gathering and analysis, problem solving, understanding and evaluating existing processes, developing and tracking measurements in a standardized manner, and making quantitative evaluations. Six Sigma methodology provides tools and techniques to ensure the success of project management. Six Sigma is a complementary management methodology that is integrated into and replaces the existing ways of determining, analyzing, and resolving problems, as well as achieving business and customer requirements objectively and methodically. Six Sigma is a robust continuous improvement strategy and process that includes cultural methodologies such as Total Quality Management, process control strategies such as Statistical Process Control, and other statistical tools. The major activities of the DMAIC of Six Sigma are:

D: Define

1. Define the who, what, and why questions of the project.
2. Write the project Charter
3. Identify the customer and translate the "voice of the customer" into requirements to measure against.
4. Create a high-level process diagram

M: Measure

1. Gather data on outputs/outcomes, processes, and inputs.
2. Identify facts and data that offer clues to quality issues.

3. Create an early sigma measure of the process.

A: Analyze

1. Analyze the data, using advanced statistical tools as needed.
2. Find the root causes of quality issues.

I: Improve

1. Solution and action stage: solve the problem and act on it.
2. May go back to the Charter to modify problem/goal statement to reflect discoveries.
3. May modify the scope of the project.
4. Implement, manage, and test solutions. Usually, solutions will be thoroughly piloted and tested before full implementation.

C: Control

1. Develop and implement monitoring process to track changes and results.
2. Create response plan in case solutions do not work as intended.
3. help management focus on appropriate metrics to get information on outcomes and processes
4. Assign project responsibilities.
5. Ensure management support for long-term goals.

Chapter 3 Methods

This chapter outlines the quantitative risk assessment methods applied in this study. Two worst credible failure scenarios on chlorine trailer were selected, five transport corridors (including the alternative corridors) with higher population density were chosen, and estimations of conditional release probability and accident rates were developed. These parameters are the base to estimate the individual risk and societal risk for the corridors along the route.

3.1 Introduction

The quantitative risk assessment utilizes descriptive, qualitative, and quantitative approaches, and major components of risk (accident frequency, release probability, and consequences) will be examined qualitatively in detail prior to quantification in order to ensure understanding. This assessment also needs to have Benchmarking against other shippers of chlorine in terms of practices and equipment will be performed for understanding and to aid in identification of potential improvements to the chlorine transport. Frequency data will be used to estimate number of serious accidents and scale of releases expected based on the total number of trips. Quantitative risk analyses (QRA) will be performed on selected segments of the current route for certain specified scenarios by using the SAFETI risk modeling software developed by DNV Technica Company.

As to the Parameters for the QRA, they include the risks from the toxic effects of chlorine exposure, the Toxic end-point that would cause fatality, scenarios leading to release from accidents and result in tank breach (small and large), selected route segments (corridors) near communities along the route, societal and individual risk estimates produced in the form of F-N curves and risk contours, respectively, and analyses to be conducted for the current state and the impact of various risk reduction combinations.

3.2 Scenario Development for Quantitative Risk Assessment

The most critical steps to conduct the quantitative risk assessment is to develop the worst credible scenarios and the data collection plan for all the parameters. The scenario development includes risk corridor selections, scenario selecting criteria, and failure scenario classification. The data collection plan shall include the background data, scenario frequencies, transport failure frequencies (accident rates and conditional release probabilities). The following steps illustrated the criteria for selecting the risky corridors along the transport route:

1. Select a route segment of 15 - 25 km (to be determined) from 1 - 3 “communities” for evaluation.
2. Route segments should border (within 5 km) or traverse highly populated areas of the

3. Origin and destination communities are probably not the most useful to evaluate for this project, since they are also at risk from the manufacturing operations which are more constant in nature, additionally, speeds on local roads in the Kaohsiung and Company A areas are generally quite low, resulting in a much lower conditional probability of release
4. Kaohsiung, Taichung, and Chungli are highly populated communities along both the current and alternate routes. For the selected communities, perform QRA on transport operation, current (base) and mitigated cases. Changhwa and Hsinchu are also evaluated since they will also be the potential alternate routes in the future. Refer to the Figure 3.1 for Taiwan Highway Map.

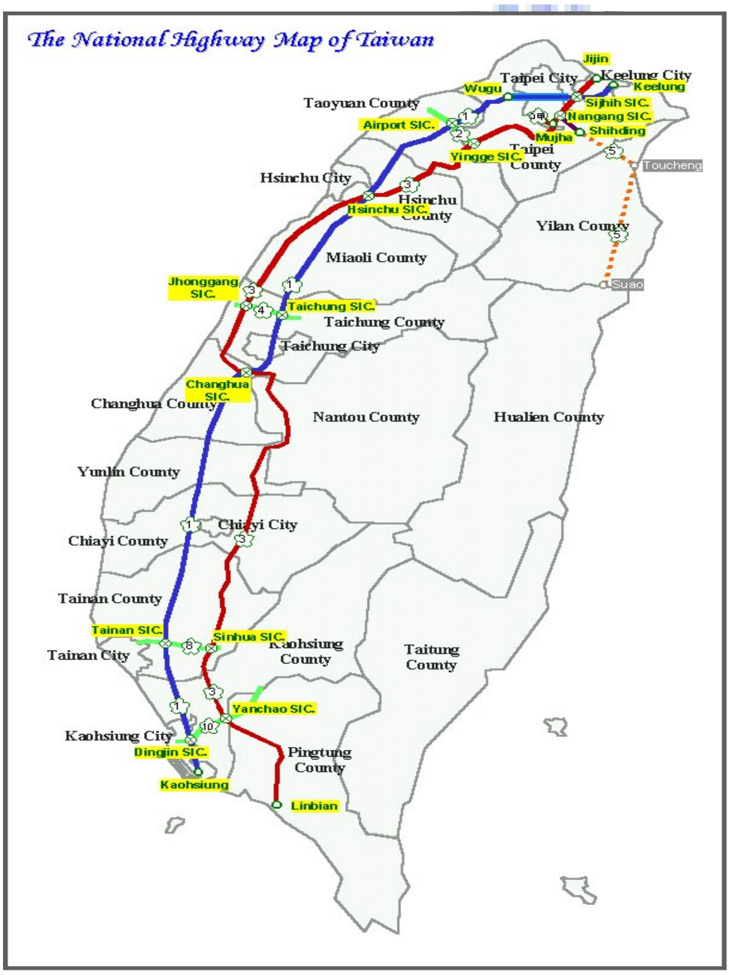


Figure 3.1 Taiwan national highway map

Herewith the selected conditions for scenarios:

1. Transport accident resulting in a small or large breach in shell of loaded tank truck.
2. Liquid chlorine released
3. Release type continuous

4. Daytime release only
5. Five stability/wind speed combinations, all wind directions considered
6. Detailed parameters (pressure, temperature, grade, etc.) to be determined
7. To the extent possible, non-residential daytime population (work places, schools, etc.), as well as highway travelers who may be exposed in the case of an accident, will be considered in addition to residential population
8. Effects of sheltering in place and emergency response will be discussed
9. Attempts to produce “confidence limits” by use of low and high estimates for frequency and consequence data will be made
10. QRA results for each segment will be presented in terms of societal and individual risk for both base and mitigated cases
11. For societal risk, the F-N curve will be compared to the Hong Kong criteria for “Potentially Hazardous Installations”
12. For individual risk, levels at 10-6 or lower (preferably 10-7 and lower) are generally considered low
13. Risk results will also be compared to background risk levels in Taiwan
14. QRA results will be used by team in combination with qualitative reviews, benchmarking results, etc. to identify needs or areas for improvement
15. To the extent possible, QRA will be used to validate the impact of proposed risk reduction measures

In general, failure scenario classification is defined as follows:

1. A 5 mm equivalent hole leakage (representative of less than or equal to a 10 mm hole size)
2. A 25 mm equivalent hole leakage(representative of 10 mm to 50 mm hole size range)
3. A 100 mm equivalent hole leakage(representative of 50 mm to 150 mm hole size range)
4. Rupture of vessel

Not all failure above are used as probable scenarios, The occurrence of vessel rupture is very rare, and consequence for 5 mm equivalent hole leakage is not obvious for overall risk contribution, therefore, two kind of failure are identified as probable scenarios:

1. Puncture results in 25 mm equivalent hole leakage of tank truck
2. Puncture results in 100 mm equivalent hole leakage of tank truck

Having defined the probable scenarios, the source term and release condition description for each scenario must be defined:

1. The type of release;
2. The release conditions;
3. The leakage hole size, mass, and duration time

4. Release frequency

The items above for each identified scenarios are outlined in scenario data sheets as shown in Table 3.1-3.4.

Scenario Name	Base-165-25 mm
Case type	Base case
Scenario Description	Puncture resulted in leakage
Release type	Continuous
Material	Chlorine
Process phase	Liquid
Process Temperature	7.2 deg. C
Process pressure	3.72 kg/cm2
Mass	16,499.8 kg
Trip number	996
Leakage hole	100 mm
Release rate	156 kg/s
Release time	105.7 sec

Table 3.1 Scenario data sheet 1

Scenario Name	Base-165-100 mm
Case type	Base case
Scenario Description	Puncture resulted in leakage
Release type	Continuous
Material	Chlorine
Process phase	Liquid
Process Temperature	7.2 deg. C
Process pressure	3.72 kg/cm2
Mass	16,499.8 kg
Trip number	996
Leakage hole	100 mm
Release rate	156 kg/s
Release time	105.7 sec

Table 3.2 Scenario data sheet 2

Scenario Name	Mitigated-165-25 mm
Case type	Mitigated case
Scenario Description	Puncture resulted in leakage
Release type	Continuous
Material	Chlorine
Process phase	Liquid
Process Temperature	7.2 deg. C
Process pressure	3.72 kg/cm2
Mass	16,499.8 kg
Trip number	996
Leakage hole	25 mm
Release rate	9.756 kg/s
Release time	1,691 sec

Table 3.3 Scenario data sheet 3

Scenario Name	Mitigated-165-100 mm
Case type	Mitigated case
Scenario Description	Puncture resulted in leakage
Release type	Continuous
Material	Chlorine
Process phase	Liquid
Process Temperature	7.2 deg. C
Process pressure	3.72 kg/cm2
Mass	16,499.8 kg
Trip number	996
Leakage hole	100 mm
Release rate	156 kg/s
Release time	105.7 sec

Table 3.4 Scenario data sheet 4

3.3 Background Data

QRA involves the integration of consequence modeling with location-specific background data. The impact of a potential release is directly related to a collection of parameters known as “background data”, which include the local atmospheric conditions and the population density.

The human impact of a chlorine release depends on the demographic patterns within the proximity of the release. The term “demographic patterns” in this study refers to the population density (i.e., persons per unit area) and the distribution of people within that area.

From this thesis, both on-road and off-road populations were analyzed. A geographic information system, GIS, is used to identify the demographic patterns change along the route from the point of production to the point of consumption of chlorine. This data is subsequently analyzed and input into population “grids”. These grids were used in the study to make an accurate account of the number of people potentially impacted by a release occurring at any point along the transport route.

The atmospheric dispersion of a hazardous material is highly related to the prevailing meteorological conditions at the time of the release. Consequently, two or more representative conditions are usually modeled for each identified scenario. The primary atmospheric factors which affect dispersion are the atmospheric stability and the wind speed. Atmospheric stability is a measure of turbulence and is classified by the Pasquill Stability Class. Class A stability represents a highly unstable atmosphere characterized by sunny, daytime conditions with a low wind speed. Unstable conditions promote the mixing of air within the vapor cloud (also called “air entrainment”) and favorable dispersion. Class F stability is a highly stable atmosphere characterized by an inversion during nighttime conditions with a low wind speed. Stable conditions inhibit air entrainment and result in unfavorable dispersion. Class D stability is a neutral atmosphere characterized by cloudy daytime or nighttime conditions with a moderate wind. Class D stability is typical for most locations and is neither favorable nor unfavorable in terms of dispersion. Higher wind speed has the effect of producing better air entrainment and more favorable dispersion.

In this study, hourly meteorological observations made over a period of one year were obtained and analyzed. Since meteorological conditions are site-specific in nature, three locations were analyzed: the city where chlorine is produced, a metropolitan area near the mid-point of the transport route, and the final destination. From statistical analysis of these observations, a series of 4 to 6 representative conditions were used. Thus, the atmospheric dispersion of each identified scenario was modeled under these varying representative conditions.

3.4 Scenario Frequencies

To evaluate the likelihood of a scenario, this study utilized historical incidents as references. Several sets of data were needed in this analysis. The overall objective is to quantify the likelihood of a scenario occurring within a given time period. Typically, a time period of one year is used. Several data sources were compiled and analyzed to determine the likelihood of an accident on the transport route. This information included overall truck accident data of Taiwan, route specific accident data, accident data of Company C's drivers. From these data several route segments are identified where accidents are more likely than the average and the segments where accidents are less likely to occur.

Fault-tree analysis was used to analyze the specific cargo tank design and to predict the likelihood of a release for a given accident. Component frequency database was utilized to estimate the frequency of tank equipment failures.

3.5 Transport Failure Frequencies

The suggested values of accident rates and conditional release probabilities for use in the chlorine transport risk analysis will be analyzed and specified.

3.5.1 Accident Rates

In a well-defined, focused transport risk assessment, especially one that will result in quantification of both frequency and consequence, it is important to use accident rates that are:

1. Representative of the actual carrier performance expected for the transport activity being analyzed.
2. Appropriate for the failure scenarios under consideration.

In this thesis, the QRA will focus only on failure of the tank trailer shell or heads due to puncture or impacts associated with a transport accident. (Other scenarios, such as valve shearing during an accident, have already been estimated to be minimal contributors to the overall risk.)

Therefore, for the purposes of this thesis, the accident rate of interest is one that may involve sufficient forces to puncture, tear, or otherwise fail the tank. Accidents such as "fender benders," that involve mild contact between automobiles or scooters with the chlorine transport unit tractor or trailer, are unlikely to generate such forces, and therefore are not included in the accident rate calculation.

The U.S. DOT counts as "recordable" accidents those that involve a) a fatality, b) an injury requiring immediate treatment away from the scene, and c) damage sufficient to require one or more of the involved vehicles to be towed away from the scene. The latter part of this definition is useful for risk analysis, because damage that is severe enough to require a tow-away of a vehicle may be assumed to have involved more forces than in a simple fender-bender. It is important to note that damage caused to an automobile involved in an accident with a heavy truck may still not involve forces sufficient to puncture a cargo tank shell. However, for the purposes of the current analysis, we will adopt the U.S. DOT definition of a recordable accident, with an adjustment for local conditions, as discussed below.

3.5.2 Adjustment of Taiwan Car Accident Rates

A major difference between the roadway conditions in the U.S. and Taiwan is the presence of a great number of scooters on the Taiwan roads. A common occurrence in Taiwan is for a scooter rider, in an attempt to move more quickly through traffic, to cut around and in front of other vehicles in an unsafe manner. As a result, thousands of accidents involving scooters occur every year, resulting in hundreds of scooter operator and passenger fatalities. The forces in such accidents may be devastating to the relatively unprotected scooter riders, but are highly unlikely to cause any damage to a chlorine tank truck. Therefore, fatalities to scooter operators and passengers resulting from an accident with a chlorine tank truck, is not included in the accident rates developed for use in the current study. Refer to Table 3.5 and Table 3.6 for Company C's accident rates in Taiwan.

Table 3.5 Company C chlorine fleet recordable accident Rate, using the definition of the U.S. DOT without scooter accidents

Year	**Trips**	**Recordable Accident (chlorine fleet of Company C)**	**Mileage (km)**	**Accident Rate**
1995	420	0	307,440	0.000
1996	580	0	424,560	0.000
1997	693	0	507,276	0.000
1998	634	0	464,088	0.000
1999	737	0	539,484	0.000
2000	836	1	611,952	1.634
2001	867	0	634,644	0.000
2002	889	0	650,748	0.000
2003	996	0	729,072	0.000
Total	6,652	1	4,869,264	0.205

Year	Recordable Accident (entire fleet of Company C)	Mileage / km	Accident Rate
1995	1	4,326,088	0.231
1996	1	4,743,650	0.211
1997	0	5,020,540	0.000
1998	4	5,419,594	0.738
1999	2	6,271,139	0.319
2000	1	6,409,125	0.156
2001	1	5,923,029	0.169
2002	0	6,338,949	0.000
2003	1	6,488,931	0.154
Total	11	50,941,045	0.216

Table 3.6 Company C entire fleet recordable accident rate

3.5.3 Accident Rate Development

In this thesis, there is only one carrier, Company C Transport, involved in the transport of Chlorine from Kaohsiung to Company A. Two accident rates are to be derived: one representative of their performance in 1995 (the “base” case), and one representative of their performance currently, after the implementation of several safety initiatives (the “mitigated” case). Upper and lower boundaries are also provided.

From 1995 through 2003, the Company C chlorine fleet drivers logged a total of 4,869,264 kilometers driven round-trip, see Table 3.5.3.1. The chlorine fleet kilometers driven have increased annually from 307 thousand in 1995 to 729 thousand in 2003. Only 1 recordable accident occurred during this 9 year period (in 2000), for an overall rate of .205 accidents per million kilometers.

Since 1995, Company C has continually implemented safety programs and initiatives, that should have both a qualitative and quantitative effect on risk reduction. However, the presence of zero numerators makes it very difficult to identify any trends that have occurred during this 9 year period.

Looking at the entire Company C fleet (including the chlorine tank truck operation), a total of 50,941,045 kilometers were logged from 1995 through 2003. The entire fleet kilometers driven have increased annually from 4.3 million in 1995 to 6.5 million in 2003. Eleven recordable accidents occurred during this 9 year period, for an overall rate of 0.216 accidents per million kilometers. This rate is very similar to that experienced just by the chlorine fleet. It is reasonable to assume that the performance of the chlorine fleet drivers would be equivalent to or better than the entire fleet, since they receive even more training and have enhanced provisions concerning work hours. In order to increase the sample size, however, we will use data for the entire Company C fleet as the basis for our accident frequency analysis, recognizing that it may be conservative.

The accident rate from 1995 through 1998 for the entire fleet was approximately 2 times higher than the rate from 1999 through 2003 (0.308 vs. 0.159). This transition period roughly coincides with the implementation of additional safety programs and measures by Company C (which due to gradual phase in and enhancements cannot be pinpointed exactly), and may also reflect an overall improvement in the Taiwan freeway system in recent years.

Accordingly, for the "base" case rate, we will use 0.308 accidents per million kilometers.

1. In order to estimate the effects of uncertainty, analyses should be run using this value as well as high and low estimates of ±50% (0.462 and 0.154). This is an arbitrary but reasonable approach since adequate data to develop actual confidence ranges are not available.
2. For the "mitigated" case rate, which accounts for the progressive programs that Company C has put in place, we will use 0.159 accidents per million kilometers.
3. As with the "base" case, analyses should be run using this rate as well as high and low estimates of ±50% (0.239 and 0.078). The lower figure may also better represent the true performance of the chlorine fleet drivers, given their advanced training and improved operating conditions.

3.5.4 Variation by Road Type and Segment

In most cases, including the current one, it is extremely difficult to generate actual accident rates experienced by a carrier along certain segments of road or even along certain types of roads.

3.5.5 Expressway vs. Local Roads

In general, local roads are more congested than expressways and therefore a higher accident rate may be expected. However, the lower speeds likely lead to a lower probability of release when an accident occurs, because the impact forces generated in the accident are usually not great. In the current study, since the focus is on failure of the tank trailer shell or heads due to puncture or impacts associated with a transport accident, only expressway corridors will be examined. Again, generally speaking, this is where higher speeds (and therefore higher impact forces) may be attained.

The accident rates provided in the previous section will be assumed to apply to expressway movements, although some of the accidents that contributed to the rate development may have occurred on local roads. This assumption will result in a more conservative, but still reasonable estimate.

3.5.6 Variation by Freeway Number and Along Freeway Segments

Ideally, the accident rates developed earlier could be adjusted to account for expected variation along different freeways or segments of those freeways. For this thesis, a corridor rather than a full route approach is being used. Table 3.7 shows the data for Expressway Number 1 from the National Police Administration for 2003.

Segment(km)	MVK	Accident No.			Accident Rate		
		A1	A2	A3	A1	A2	A3
Kaohsiung （356~367）	19,855	1	16	680	0.0005	0.00081	0.034
Taichung （174~188）		2	17	450	0.001	0.00086	0.023
Chungli（52~64）		4	21	759	0.0002	0.0011	0.038

Table 3.7 Accident numbers and rates of three different road segments

The definitions for A1 (fatality within 24 hours), A2 (injury), and A3 (property damage) do not correspond directly with the definition we are using for the current analysis. However, it can be seen that the A3 accident rate in the Taichung corridor may be slightly less than in the Kaohsiung or Chungli corridors. While we could adjust our accident rate to account for an expected difference, the rate variation is not large enough to justify this added detail. (Also, the variation among different accident outcomes is not consistent within corridors, which further complicates any adjustment.)

Perhaps of greater interest for evaluation of route alternatives would be accident rate differences between the various National Expressways that might be utilized. Since Expressway Number 3 has only recently been in operation, it may require some time before adequate data are collected. Development of a table similar to above might also be valuable in evaluating potential differences between accident rates on the “base” and “mitigated” case corridors (Changhwa and Hsinchu).

3.6 Conditional Release Probabilities

Conditional release probabilities, that is, the chance that a transport package will suffer loss of lading given that it is involved in an accident, are more difficult to develop than accident rates. Many databases exist that record package failures, but without an understanding of how many packages are involved in accidents (and do or do not fail), a conditional release estimate based on actual performance cannot be derived.

In the U.S., an ongoing initiative among railroad equipment suppliers and the major railroad industry organization has allowed the development of conditional release probabilities for rail tank cars that are involved in accidents. However, no such initiative exists for tank trucks. As a result, tank truck conditional release probabilities are often developed based on professional experience and judgment, engineering analysis of tank truck design, extrapolation from rail tank car performance, and results of focused analyses performed by other researchers to investigate a particular issue. We will use all of these to develop representative conditional release probabilities for the current study.

3.7 Mechanisms of Tank Truck Failure

In general, the most common failure mechanisms of concern given that a serious tank truck accident has occurred are impact, resulting in tank wall failure through deformation or tearing; puncture, resulting in a tank wall failure by a penetrating object; fire involvement, resulting in over-pressurization of the tank and activation of the relief valve (and in the most serious cases, BLEVE); and shearing of (or other damage to) valves or fittings. Crush forces during overturn have been analyzed and determined to be unlikely to fail tank walls of heavy pressure tanks such as used to transport liquefied compressed gases.

3.8 Conditional Release Probability Development

Using Geffen's [8] fault tree approach, we are interested in the following event sequences (all beginning with an accident occurring):

1. Puncture probe produced in accident – Puncture probe contacts tank shell – Puncture probe fails tank shell
2. Impact forces produced in accident – Tank wall experiences impact forces – Impact forces fail normal tank wall

3. Impact forces produced in accident – Tank end experiences impact forces – Impact forces fail normal tank end
4. Impact forces produced in accident – Tank head experiences impact forces – Impact forces fail normal tank head

There are also 3 scenarios involving impact forces failing a defective tank wall, end, or head.

However, these are generally of extremely low probability (in the range of 1.0 x 10^{-10} or 10^{-11}), and will not be considered in the current analysis.

Probabilities for each of the events in the 4 sequences listed above are derived from the Geffen's report, and are presented below. There is an important difference between their approach and the one used in development of the estimates below. In the Geffen's report, the terms involving the fraction of truck collisions, for any of the impact event sequences, were generally based on truck to truck, train to truck, and automobile to truck collisions, all assuming that the truck remained upright. In most cases, automobile to truck collisions are unlikely to directly impact the cargo tank wall, end, or head, but more likely would impact the support frame and appurtenances, such as the trailer support legs, tires, or rear-end protection. It is only in the case of truck to truck, train to truck, or truck to object collisions that direct contact to the tank during impact might be expected. Therefore, I have adjusted the fraction term in event sequences Number 2 through Number 4 to reflect only those scenarios.

Additionally, for event sequence Number 4, in a head-on collision of a tractor-trailer to any other vehicle, it would most times be the tractor (power unit) impacted directly, not the tank head. However, I have not made any additional adjustments to this sequence, because there are accident scenarios where the tank head could plausibly suffer the impact force (such as during a jackknife).

3.8.1 Event Sequence Number 1

From Geffen's report on the probability of a truck collision with another vehicle, train, or stationary object, given an accident, it's estimated that the puncture probe produced in an accident is 0.802. From the extrapolation of Geffen's report for a package wall thickness of 0.7 inches of steel (effective thickness shell plus jacket), it's estimated that the puncture probe contacts tank shell is 0.207. From Geffen's report, based on rail tank-car puncture data and extended to tank trucks, it's estimated that the puncture probe fails tank shell is 0.01.

Based on the estimations above, the conditional probability of a release due to puncture is 0.802 x 0.207 x 0.01 = 0.0017.

3.8.2 Event Sequence Number 2

From Geffen’s report, it’s estimated that the probability of impact forces produced in accident is 0.802. For the fraction of truck collisions that involve side-on impact, it’s estimated that the probability of tank wall experiences impact forces is 0.024. For the probability of impact forces fail tank wall is estimated 0.01.

Based on an estimated threshold puncture velocity of 40 kilometers per hour, from industry studies; Geffen’s report estimates this fraction of accidents to experience this velocity change or higher, for a 36,000 kilogram truck.

Based on the estimations above, the conditional probability of a release due to wall impact: 0.802 x 0.024 x 0.01 = 0.0002

3.8.3 Event Sequence Number 3

From Geffen’s report on the probability of a truck collision with another vehicle, train, or stationary object, given an accident, it’s estimated that the puncture probe produced in an accident is 0.802. For the probability that tank end experiences impact forces is 0.081. For the probability that the fraction of truck collisions that involves rear-end impact is 0.01.

Based on an estimated threshold puncture velocity of 40 kilometers per hour, from industry studies; Geffen’s report estimates this fraction of accidents to experience this velocity change or higher, for a 36,000 kilogram truck.

Based on the estimations above, the conditional probability of a release due to wall impact: 0.802 x 0.081 x 0.01 = 0.0006

3.8.4 Event Sequence Number 4

From Geffen’s report on the probability of a truck collision with another vehicle, train, or stationary object, given an accident, it’s estimated that the puncture probe produced in an accident is 0.802. For the probability that tank head experiences impact forces is 0.288. For the probability of the fraction of truck collisions that involves head impact is 0.01.

Based on an estimated threshold puncture velocity of 48.3 kilometers per hour, from industry studies; Geffen’s report estimates this fraction of accidents to experience this velocity change or higher, for a 36,000 kilogram truck.

Based on the estimations above, the conditional probability of a release due to wall impact: 0.802 x 0.288 x 0.01 = 0.0023

All these 4 event sequences and the data are illustrated in the following table, Conditional Probabilities on four identified event sequences.

Conditional Probabilities	Puncture Probe Impact probability	Probe Contact probability	Failure probability	Conditional probability of a release
Event 1 – tank shell impact	0.802	0.207	0.01	0.0017
Event 2 – tank wall impact	0.802	0.024	0.01	0.0002
Event 3 – tank end impact	0.802	0.081	0.01	0.0006
Event 4 – tank head impact	0.802	0.288	0.01	0.0023

Table 3.8 Conditional probabilities on four identified event sequences

3.8.5 Total Conditional Probability of a Release Given a Truck Accident Occurs:

0.0017 + 0.0002 + 0.0006 + 0.0023 = 0.0048

Although the Geffen's report may be outdated in terms of crash analysis, the value derived above appears reasonable, although somewhat low compared to other estimates that have appeared in the literature. However, it is evident from available incident reports that accident-caused releases from compressed gas cargo tanks are quite rare.

An event sequence that was not considered in these reports was one of a tractor trailer overturning and incurring damage to tank walls, head, or end by impacting (or being impacted by) another object. Geffen stated that these accidents more usually involve a gradual slowing of the vehicle through a series of low-level impacts and ground level friction, rather than a severe single impact. The percentage of truck accidents resulting in non-collision outcomes (such as overturning) was 19.8. If we assume that 1% of these non-collision outcomes result in release of product due to tank wall, head, or end impact and failure, our conditional release probability above would be increased by .002 (0.198 x 0.01), for a total release probability of 0.0068.

3.8.6 Spill Size Distribution

It is assumed, based on other studies, that approximately 90% of punctures incurred in accidents resulted in a 25 mm equivalent diameter hole, and 10% resulted in a 100 mm equivalent diameter hole. We will use these assumptions. It’s been checked for more updated information to ensure that we are using a reasonable spill size distribution.

3.8.7 Reasonable Rates and Conditional Release Probabilities in Taiwan

It must be recognized that the estimates used in this analysis are generally not precise. Additionally, it is impossible to quantify all factors that could contribute to the components of the risk equation. Therefore, chosen estimates based on historical data, engineering principles and calculations, and professional experience and judgment could be considered reasonable.

The rates that originally proposed for the chlorine fleet were 0.308 accidents per million kilometers for the base case (1995 - 1998), and 0.159 for the mitigated case (1999 - 2003). Low and high estimates for each of these cases were based on plus or minus 50% of the average rate. These estimates were based on the performance of the entire Company C truck fleet, which logs considerably more miles than the chlorine fleet alone. The true performance of the chlorine fleet is likely to be better than that of the entire fleet, since the chlorine drivers undergo more training and have special work schedules to reduce fatigue, inattention, and other potential driving problems.

However, the average rates as developed are quite representative of the performance of the very best U.S. fleets that have extensive safety programs. Therefore, these rates are considered reasonable for use in the current study without further adjustment. It must be recognized that the actual rate for the chlorine fleet could be considerably lower than for the entire fleet, based on the special safety programs and driver initiatives.

In the discussion of results, we will therefore focus on the results using the low estimates (base case: 0.154; mitigated case: 0.080). Results using the average estimates are considered to be quite conservative.

The accident rates for the various corridors should not be adjusted at this time, because sufficient data do not exist to compare specific corridors, or even to compare National Expressway Number 1 (our base case which has been used since the beginning of shipments) to other roads. The government of Taiwan does not calculate expressway specific or location (corridor) specific rates; rather, the same denominator of vehicle miles is used for all calculations. In order to accurately understand the accident rate differences on various expressways, both the numerators and denominators must reflect those specific to each road. Additionally, Expressway Number 3 is fairly new, and sufficient time may not have passed to develop reliable accident rates, even if the correct data collection processes were in place. It may be postulated that the accident rate on Expressway Number 3 will be lower than on

Number 1, due to improvements in highway design (such as less steep grades, wider lanes, and improved surfacing), weather conditions (less fog), and traffic patterns (less congestion), but at this point these are only conjecture. However, as Expressway Number 3 becomes more widely used, the traffic density and patterns could change, and also accidents could be more serious if speeds are increased. More time is required for an understanding of the dynamics of Expressway Number 3 to be developed. However, we can assume that the Company C chlorine drivers will continue to exhibit excellent driving behavior on any route, and therefore use the same accident rates as described above for corridors on both the existing and new potential route.

The conditional release probability (estimated as 0.0068 overall; 10% "large" hole, 90% small hole) is not likely to change considerably by corridor unless the average speeds are exceptionally lower or higher in certain locations. In fact, while the speeds traveled by Company C drivers in the Kaohsiung and Chungli corridors (55 - 60 kilometers per hour) are somewhat lower than those traveled in the other corridors (70 - 75 kilometers per hour), this still exceeds the estimated threshold puncture velocity of 40 kilometers per hour described in the Sandia report. In other words, given the right circumstances, we could expect a chlorine trailer to be punctured at speeds at or above 40 kilometers per hour, so no adjustments to the Kaohsiung and Chungli corridor release probabilities are currently justified. On the other hand, based on the construction of the chlorine trailers as well as the U.S. accident and release data for similarly constructed tanks, we again acknowledge that the average release probabilities generated for this study are likely to be quite conservative. Therefore, as with the accident rate data, we will again focus on the results using the low estimates of 0.00034 for a large hole and 0.0031 for a small hole.

3.9 Scenario Consequences

The goal of analyzing scenario consequences is to predict the number of people impacted by all possible outcomes of the scenarios. This study uses the fatality risk level as a convention as opposed to an injury risk level. In this study, consequence models are used to predict the size and shape of a toxic cloud, as well as chlorine concentration profiles within the cloud. Important factors which influence these calculations include: the release phase (vapor, liquid, or heterogeneous), the release temperature, rate of release, release velocity, release orientation (horizontal or vertical), atmospheric stability, wind speed, etc. Human response to airborne chlorine is calculated using a dose-response, or probit analysis. This analysis considers both the airborne chlorine concentration and the exposure duration in estimating the proportion of the exposed population which may be fatally impacted.

To gain further insight into the significance of the transport accident scenarios, a discussion of several factors which influence the likelihood and consequence is required. These factors include the length of the route, frequency of deliveries, probability of accident, etc. The following questions and answers facilitate the discussion of these factors.

Question 1) How many kilometers are covered each time a trailer hauls a load of chlorine from the production site to the point of consumption?

Answer 1) Based on observations of the route, the truck travels approximately 350 kilometers from Company B to Company A.

Question 2) How many kilometers are driven each year on the chlorine transport route?

Answer 2) Based on the production level of approximately 750 loads per year, (i.e., 2.1 loads per day): 750 trailer loads per year x 350 km per load = 262,500 km per year

Question 3) How likely is it to have a traffic accident while on route?

Answer 3) Based on the average expressway accident rate, there will be 0.075 accidents per million kilometers traveled. 0.075 accidents per one million km x 0.2625 million km per year = 0.02 accident per year. This figure indicates that an accident will occur approximately every 50 years of operation.

Question 4) How likely is it to have a chlorine release while on route?

Answer 4) Since most roadway accidents are relatively low in severity, it is unlikely that an accident will cause a chlorine release. Base on accident statistics and an engineering analysis of the cargo tank design, it is estimated that there is a 0.435 probability of a chlorine release following an accident: 0.02 accidents per year x 0.00435 chlorine release per accident = 0.0000862 chlorine release per year. This indicates that a chlorine release will occur approximately every 11,600 years of operation. Since the average lifetime of a production facility is about 20 to 40 years, a chlorine release from this transport route during the lifetime of the project is quite unlikely. However, it is accurate to state that there is a 1 in 11,600 chance of a release during each year of operation.

Question 5) What are the consequences of a chlorine release following an accident?

Answer 5) There are numerous potential outcomes of a chlorine release following an accident depending on the severity of the accident. The most likely outcome is a medium leak caused by a puncture of the tank. This leak might empty the chlorine trailer in about 30 minutes and result in an average of 78 fatalities. A similar consequence would result from the shearing of one of the valve connections on the trailer, although this event is even less likely than puncturing the tank.

The most severe outcome is a large hole in the tank caused by a puncture. Although very rare, this event would empty the tank in approximately 2 minutes and result in an average of 326 fatalities.
Of course, the events described above could occur anywhere along the route. If a release were to occur in a heavily populated area such as the city where Company B is located, more fatalities might be expected. If a release were to occur in a sparsely populated rural area, fewer fatalities might be expected.

There is also the potential for relatively minor equipment leaks, not accident related, occurring while in transit. These failures are more likely to occur but unlikely to result in a fatality. In addition, the driver is trained to mitigate the effects of minor leaks and additional response capabilities are stationed at three points along the route.

Question 6) Which areas of the route are at a higher level of risk?

Answer 6) The density of people living and working along the route was the primary factor which influence transport risk. The segments of the road which pass through densely populated areas such as the major cities contributed more to overall transport risk than did the rural areas.

On the expressway north of the metropolitan located near the mid-section of Taiwan, there are hilly areas with steep slopes. These areas are identified to have higher than average accident rates, and thus more likely to result in a chlorine release than the flat terrain south of the city. However, these hilly areas also are sparsely populated relative to the population centers of the major cities along the transport route. In addition, hilly terrain generates wind turbulence which aids the dispersion of airborne chlorine.

The population variation and terrain effects have a larger impact on risk than the increase in accident frequency. Thus, road segments in the hilly terrain north of the city located in the middle section of Taiwan does not contribute significantly to transport risk.

Question 7) How does driver training influence the transport risk?

Answer 7) Drivers of the trucks hauling chlorine from Company B to Company A are employed by Company C, a contractor to the chlorine producer. Only employees with good driving records are selected for this assignment. They are trained in the hazards of chlorine and how to respond in the unlikely event of a release while on route.

Better drivers result in fewer roadway accidents and a lower probability of a chlorine release. Several sources of accident data are analyzed in order to determine the likelihood of these drivers being involved in an accident. The data indicate a range in the accident likelihood of about a factor of 10. The chlorine truck drivers are assessed to be in the upper part of this range based on their level of training and driving skills.

Chapter 4 Results and Discussions

This thesis applies SAFETI, the quantitative risk modeling software to calculate the individual risk and societal risk for the selected scenarios and corridors (including the corridors on the alternative route) along the transport route. Two different time frames were selected as the base case (from Year 1995 to 1998), and mitigated case (from 1999 to 2003) were developed to verify the effectiveness of risk reduction measures from all involved parties on the chlorine transport. Six Sigma methodology and statistics is applied to identify the key variables of the risk reduction measures taken in 1996-2003. Further risk reduction plan can then further developed based on the key variables identified from the methodology to mitigate the risk may have increased from future fleet increments due to stronger market needs.

4.1 Application of Software for Risk Estimation

For risk estimation, This thesis is accomplished using SAFETI (Software for the Assessment of Flammable, Explosive, and Toxic Impact). SAFETI contains a wide range of models which can be employed to calculate scenario consequences and frequencies. This software also contains a database which tracks the frequency and consequence of each scenario outcome.

The Base Case was developed to determine potential expected risk resulting from accident rate records of Company C tank truck transport during 1995~1998. Scenario data sheets in which include process condition, release condition and release frequency calculations for base cases are shown in Table 3.1-3.2.

The Mitigated Case was developed to determine Potential expected risk resulting from accident rate records of Company C's tank truck transport based on 1999~2003. Scenario data sheets in which process condition, release condition and release frequency calculation are included for mitigated case are shown as Table 3.3-3.4.

Further quantitative risk assessments were also conducted to evaluate the risk increment for the increased chlorine transport trips because of business expansion and corridor changes along the route because of population density considerations.

Risk Summation Along Transport Route and Comparison Between Base Case and Mitigated Case

4.1.1 Kaohsiung Corridor Societal Risk, F-N Curve

The F-N curve for the base case is shown in Figure 4.1, the F-N curve for the mitigated case is shown in Figure 4.2. The F-N curves of Figure 4.1 and Figure 4.2 present overall risk that each risk of

1 (KM) segment is combined and accumulated through total length of evaluated corridor. Obviously, through Company C company's effort in continuously conducting safety improvement program during 1996~2003, risk reduction is apparent for transport from COMPANY B to COMPANY A. Detailed resulted F-N data comparison of base case versus mitigated case in Kaohsiung corridor are outlined in Table 4.1.

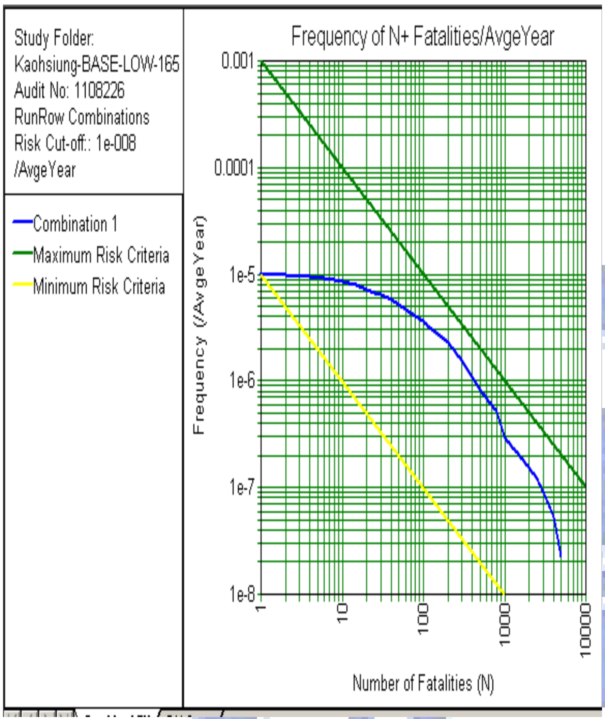


Figure 4.1 F-N curve for chlorine transport in Kaohsiung corridor for the base case

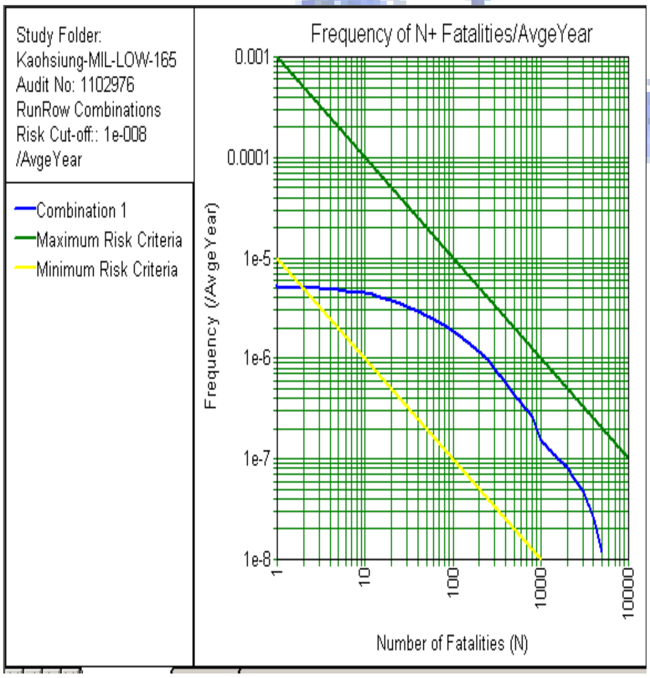


Figure 4.2 F-N curve for chlorine transport in Kaohsiung corridor on the mitigated case

	Cumulative frequency of fatalities equal to and above N per year (× 10^6)			
	N=1	N=10	N=100	N=1,000
Base Case	10	8	3.5	0.3
Mitigated Case	5	4	2	0.16

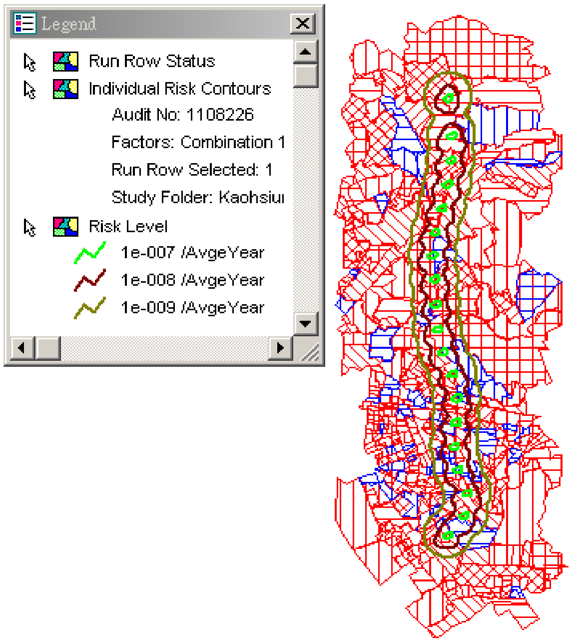
Table 4.1 F-N data comparison of base case versus mitigated case in Kaohsiung corridor.

Table 4.1 indicates that transport related release risk of mitigated case resulting in 1or more fatalities, 10 or more fatalities are each 2 times less than base case in Kaohsiung corridor. Similarly, the transport related release risk of mitigated case resulting in 100 or more fatalities, 1000 or more fatalities are each about 1.8 times less than base case in Kaohsiung corridor.

It must be emphasized that the F-N resulted curve of transport risk of Base case and mitigated case in Kaohsiung corridor are within the As Low As Reasonably Practical (ALARP) range for Hong Kong risk criteria up to a fatality level of 1,000 or more fatalities. The societal risk associated with the chlorine transport in Kaohsiung corridor is within acceptable levels. But for the "ALARP" concept that the risk must be reduced as could as possible in order to let F-N curve below Hong Kong risk criteria, continuous risk improvement is necessary to attain Hong Kong risk criteria.

4.1.2 Kaohsiung Corridor Individual Risk:

The likelihood of fatality for a hypothetical person who located at a specific point is visualized by individual risk contours. Certainly, the geographic representation of risk contour allows for the estimation of risk to who stays in specific work place, schools, and other denser population locations. The individual risk contours for the area surround Kaohsiung corridor as a result of chlorine transport based on base case are drawn on the Figure 4.3. The highest risk level is 10^{-7} or 1 chance of fatality in 10^7 per year. The lowest risk level is 10^{-9} or 1 chance of fatality in 10^9 per year. The shape of these contours is primarily dependent on the local wind pattern in the area; the individual risk contours for the area surround Kaohsiung corridor as a result of chlorine transport based on mitigated case are drawn on the Figure 4.4. The highest risk level is 10^{-8} or 1 chance of fatality in 10^8 per year. The lowest risk level is 10^{-9} or 1 chance of fatality in 10^9 per year. As a matter of fact, both highest risk levels in mitigated case and base case are less than acceptable highest risk level of 10^{-6} per year, therefore, the individual risk in Kaohsiung corridor is acceptable. In mitigated case, the highest risk level is 10 times less than highest risk level in base case. Apparently, safety improvement program being ran efficiently in Company C company during 1996~2003, the target of risk reduction has been completed.



Legend

Run Row Status

Individual Risk Contours

Audit No: 1108226

Factors: Combination 1

Run Row Selected: 1

Study Folder: Kaohsiu

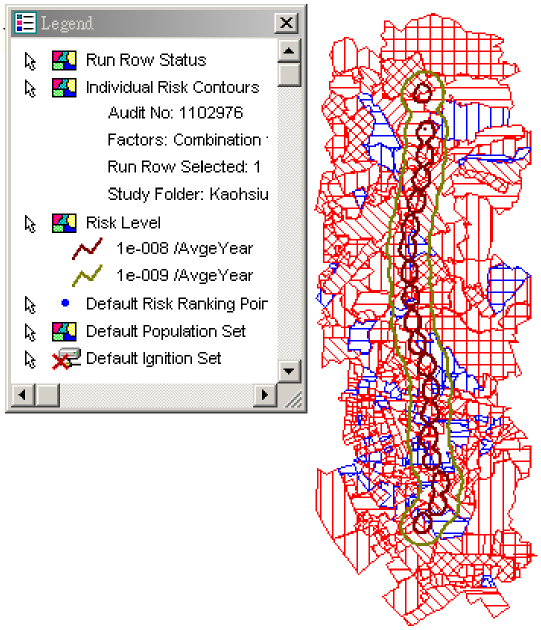
Risk Level

1e-007 /AvgeYear

1e-008 /AvgeYear

1e-009 /AvgeYear

Figure.4.3 The individual risk contours in Kaohsiung corridor for the base case



Legend

Run Row Status

Individual Risk Contours

Audit No: 1102976

Factors: Combination

Run Row Selected: 1

Study Folder: Kaohsiu

Risk Level

1e-008 /AvgeYear

1e-009 /AvgeYear

Default Risk Ranking Poir

Default Population Set

Default Ignition Set

Figure 4.4 The individual risk contours in Kaohsiung corridor for the mitigated case

4.1.3 Taichung Corridor Societal Risk, F-N Curve

The F-N curve for the base case is shown in Figure 4.5, the F-N curve for the mitigated case is shown in Figure 4.6. The F-N curves of Figure 4.5 and Figure 4.6 present overall risk that each risk of 1 (KM) segment is combined and accumulated through total length of evaluated corridor. Obviously, through Company C company's effort in continuously conducting safety improvement program during 1996~2003, risk reduction is apparent for transport from COMPANY B to COMPANY A. Detailed resulted F-N data comparison of base case versus mitigated case in Taichung corridor is outlined in Table 4.2. Table 4.2 indicates that transport related release risk of mitigated case resulting in 1or more fatalities, 10 or more fatalities, 100 or more fatalities are each about 2 times less than base case in Taichung corridor. It must be emphasized that the F-N resulted curve of transport risk of Base case and mitigated case in Taichung corridor are within the As Low As Reasonably Practical (ALARP) range for Hong Kong risk criteria up to a fatality level of 1,000 or more fatalities. The societal risk associated with the chlorine transport in Taichung corridor is within acceptable levels. But for the "ALARP" concept that the risk must be reduced as could as possible in order to let F-N curve below Hong Kong risk criteria, continuous risk improvement is necessary to approach Hong Kong risk criteria.

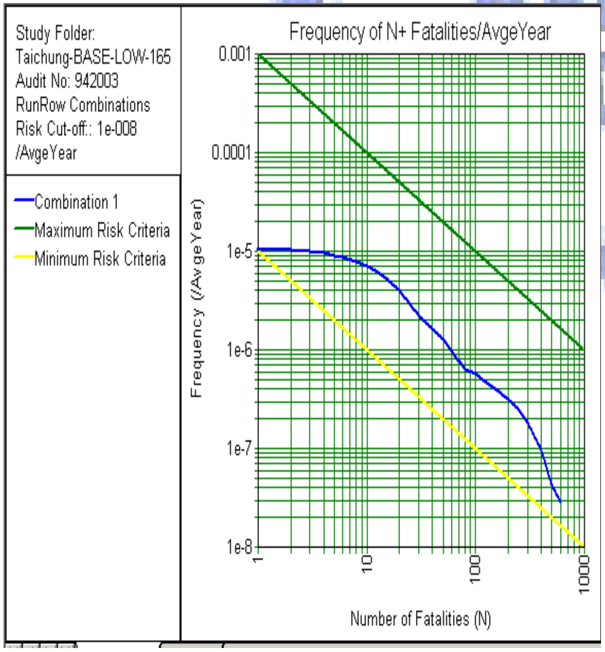


Figure 4.5 F-N curve for chlorine transport in Taichung corridor for the base case

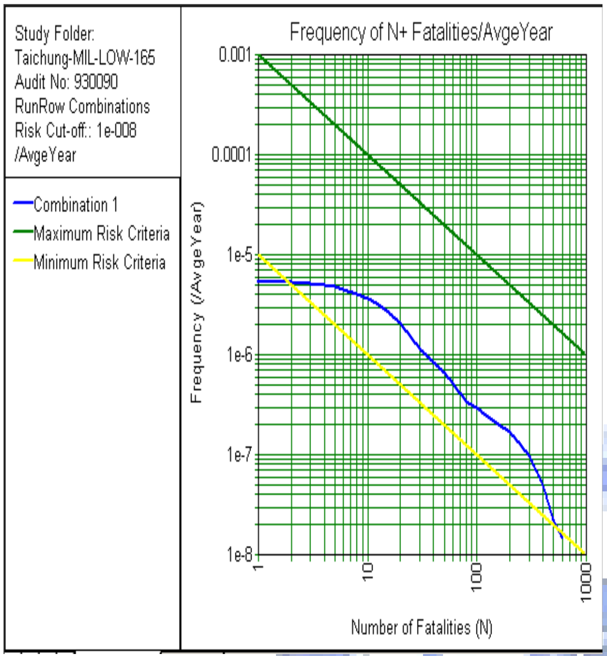


Figure 4.6 F-N curve for chlorine transport in Taichung corridor for the mitigated case

	Cumulative frequency of fatalities equal to and above N per year (× 10^6)			
	N=1	N=10	N=100	N=1,000
Base Case	10	7	0.6	0
Mitigated Case	5	3.8	0.3	0

Table 4.2 F-N data comparison of base case versus mitigated case in Taichung corridor

4.1.4 Taichung Corridor Individual Risk

The likelihood of fatality for a hypothetical person who located at a specific point is visualized by individual risk contours. Certainly, the geographic representation of risk contour allows for the estimation of risk to who stays in specific work place, schools, and other denser population locations. The individual risk contours for the area surround Taichung corridor as a result of chlorine transport based on base case are drawn on the Figure 4.7. The highest risk level is 10^{-7} or 1 chance of fatality in 10^7 per year. The lowest risk level is 10^{-9} or 1 chance of fatality in 10^9 per year. The shape of these contours is primarily dependent on the local wind pattern in the area; the individual risk contours for the area surround

Taichung corridor as a result of chlorine transport based on mitigated case are drawn on the Figure 4.8. The highest risk level is 10^{-7} or 1 chance of fatality in 10^{7} per year. The lowest risk level is 10^{-9} or 1 chance of fatality in 10^{9} per year. As a matter of fact, both highest risk levels in mitigated case and base case are less than acceptable highest risk level of 10^{-6} per year, therefore, the individual risk in Taichung corridor is acceptable. In mitigated case, the downwind distance of highest and lowest risk level are apparently smaller than the downwind distance of highest risk level and lowest risk level in base case. Apparently, safety improvement program being run efficiently in Company C company during 1996~2003, the target of risk reduction has been completed.

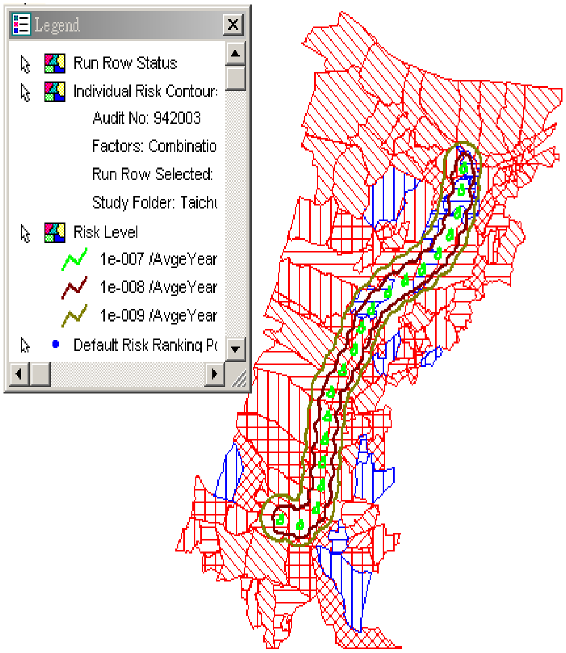


Figure.4.7 The individual risk contours in Taichung corridor for the base case.

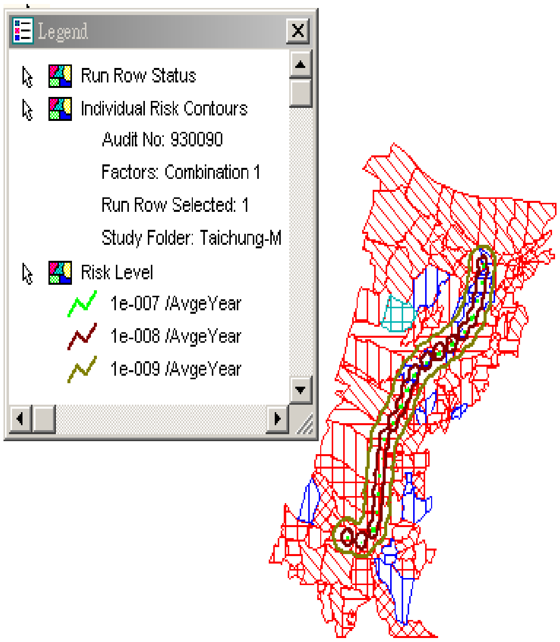


Figure 4.8 The individual risk contours in Taichung corridor for the mitigated case

4.1.5 Chungli Corridor Societal Risk, F-N Curve

The F-N curve for the base case is shown in Figure 4.9, the F-N curve for the mitigated case is shown in Figure 4.10. The F-N curves of Figure 4.9 and Figure 4.10 present overall risk that each risk of 1 (KM) segment is combined and accumulated through total length of evaluated corridor. Obviously, through Company C company’s effort in continuously conducting safety improvement program during 1996~2003, risk reduction is apparent for transport in Chungli corridor. Detailed resulted F-N data comparison of base case versus mitigated case in Taichung corridor is outlined in Table 4.3**.** Table 4.3 indicates that transport related release risk of mitigated case resulting in 1or more fatalities, 10 or more fatalities, 100 or more fatalities, 100 or more fatalities are each about 1.7 to 2 times less than base case in Taichung corridor. It must be emphasized that the F-N resulted curve of transport risk of base case and mitigated case in Taichung corridor are within the As Low As Reasonably Practical (ALARP) range for Hong Kong risk criteria up to a fatality level of 1,000 or more fatalities. The societal risk associated with the chlorine transport in Chungli corridor is within acceptable levels. But for the “ALARP” concept that the risk must be reduced as could as possible in order to let F-N curve below Hong Kong risk criteria, continuous risk improvement is necessary to approach Hong Kong risk criteria.

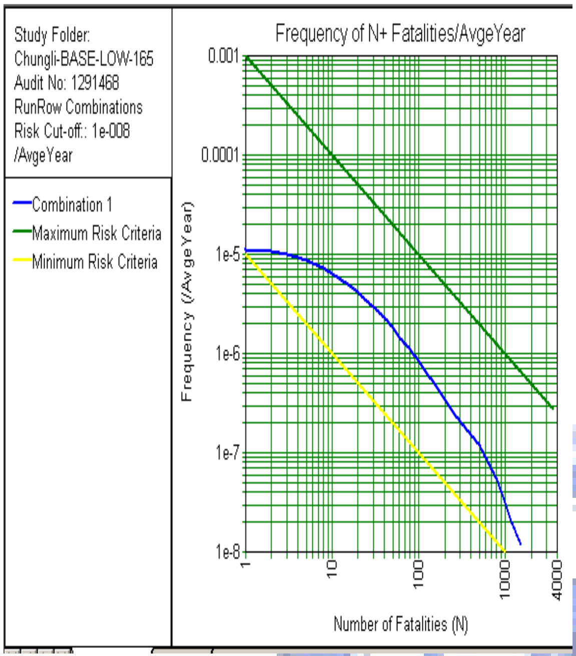


Figure 4.9 F-N curve for chlorine transport in Chungli corridor for the base case

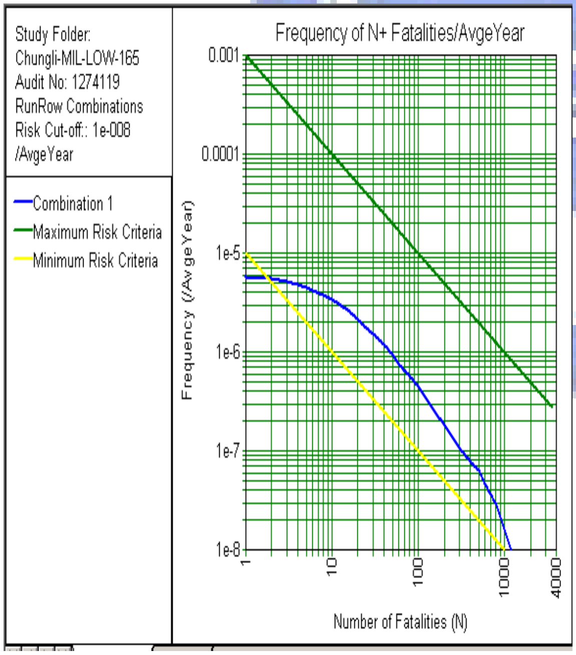


Figure 4.10 F-N curve for chlorine transport in Chungli corridor for the mitigated case

	Cumulative frequency of fatalities equal to and above N per year ($\times 10^6$)			
	N=1	N=10	N=100	N=1,000
Base Case	10	6	0.8	0.03
Mitigated Case	6	3.5	0.4	0.018

Table 4.3 F-N data comparison of base case versus mitigated case in Chungli corridor

4.1.6 Chungli Corridor Individual Risk

The likelihood of fatality for a hypothetical person who located at a specific point is visualized by individual risk contours. Certainly, the geographic representation of risk contour allows for the estimation of risk to who stays in specific work place, schools, and other denser population locations. The individual risk contours for the area surround Chungli corridor as a result of chlorine transport based on base case are drawn on the Figure 4.11. The highest risk level is 10^{-7} or 1 chance of fatality in 10^{7} per year. The lowest risk level is 10^{-9} or 1 chance of fatality in 10^{9} per year. The shape of these contours is primarily dependent on the local wind pattern in the area; the individual risk contours for the area surround Chungli corridor as a result of chlorine transport based on mitigated case are drawn on the Figure 4.12. The highest risk level is 10^{-7} or 1 chance of fatality in 10^{7} per year. The lowest risk level is 10^{-9} or 1 chance of fatality in 10^{9} per year. As a matter of fact, both highest risk levels in mitigated case and base case are less than acceptable highest risk level of 10^{-6} per year, therefore, the individual risk in Chungli corridor is acceptable. In mitigated case, the downwind distance of highest risk level is apparently smaller than the downwind distance of highest risk level in base case. Apparently, the target of risk reduction has been completed since safety improvement program being run efficiently in Company C during 1996~2003.

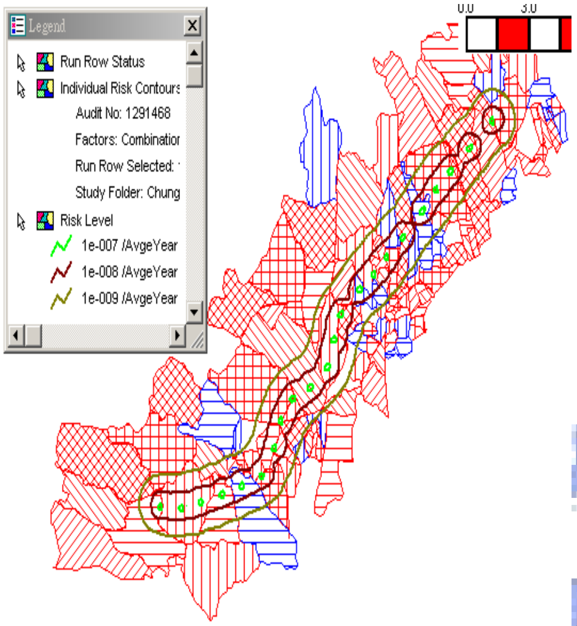


Figure 4.11 The individual risk contours in Chungli corridor for the base case

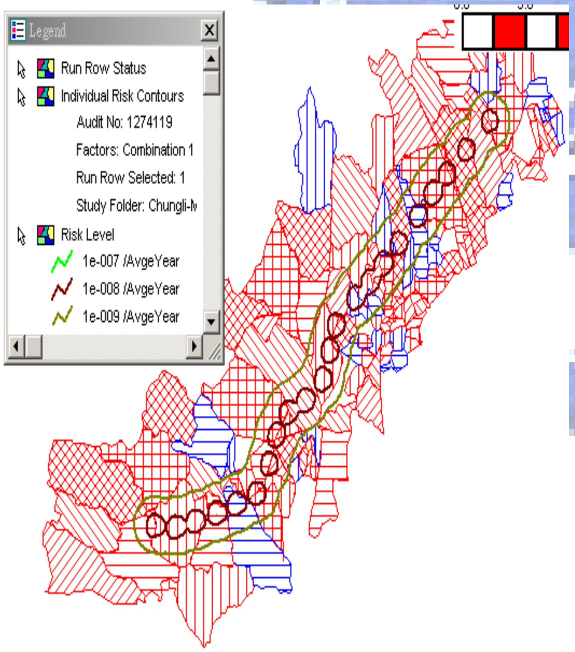


Figure 4.12 The individual risk contours in Chungli corridor for the mitigated case

4.1.7 Changhwa Corridor Societal Risk, F-N Curve

The F-N curve for the base case is shown in Figure 4.13, the F-N curve for the mitigated case is shown in Figure 4.14. The F-N curves of Figure 4.13 and Figure 4.14 present overall risk that each risk of 1 (KM) segment is combined and accumulated through total length of evaluated corridor. Obviously, through loglat company's effort in continuously conducting safety improvement program during 1996~2003, risk reduction is apparent for transport in Changhwa corridor. Detailed resulted F-N data comparison of base case versus mitigated case in Changhwa corridor is outlined in Table 4.4. Table 4.4 indicates that transport related release risk of mitigated case resulting in 1or more fatalities, 10 or more fatalities, 100 or more fatalities, 100 or more fatalities are each about 1.8 to 2.1 times less than base case in Changhwa corridor. It must be emphasized that the F-N resulted curve of transport risk of Base case and mitigated case in Changhwa corridor are within the As Low As Reasonably Practical (ALARP) range for Hong Kong risk criteria up to a fatality level of 1,000 or more fatalities. The societal risk associated with the chlorine transport in Changhwa corridor is within acceptable levels. But for the "ALARP" concept that the risk must be reduced as could as possible in order to let F-N curve below Hong Kong risk criteria, continuous risk improvement is necessary to approach Hong Kong risk criteria.

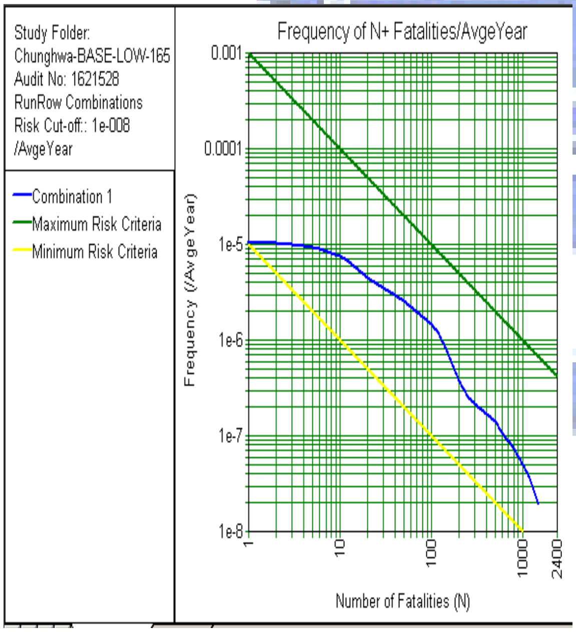


Figure 4.13 F-N curve for chlorine transport in Changhwa corridor for the base case

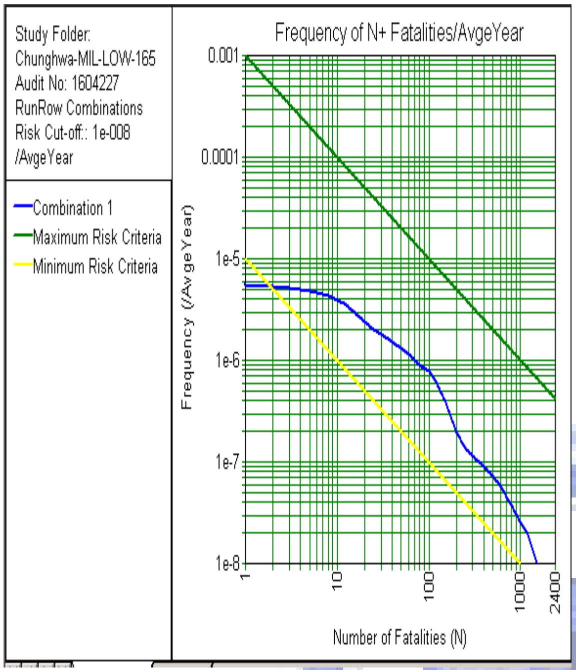


Figure 4.14 F-N curve for chlorine transport in Changhwa corridor for the mitigated case

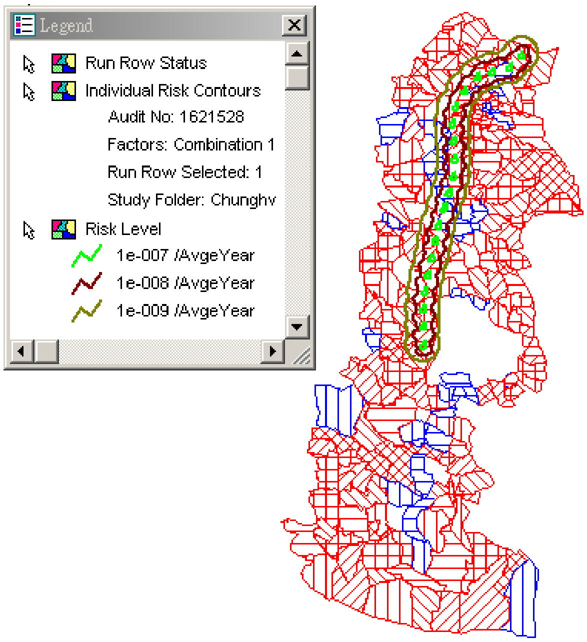
	Cumulative frequency of fatalities equal to and above N per year ($\times 10^{6}$)			
	N=1	N=10	N=100	N=1,000
Base Case	10	7	1.5	0.05
Mitigated Case	5.5	4	0.7	0.025

Table 4.4 F-N data comparison of base case versus mitigated case in Changhwa corridor.

4.1.8 Changhwa Corridor Individual Risk

The likelihood of fatality for a hypothetical person who located at a specific point is visualized by individual risk contours. Certainly, the geographic representation of risk contour allows for the estimation of risk to who stays in specific work place, schools, and other denser population locations. The individual risk contours for the area surround Changhwa corridor as a result of chlorine transport based on base case are drawn on the Figure 4.15. The highest risk level is 10^{-7} or 1 chance of fatality in 10^{7} per year.

The lowest risk level is 10^{-9} or 1 chance of fatality in 10^{9} per year. The shape of these contours is primarily dependent on the local wind pattern in the area; the individual risk contours for the area surround Changhwa corridor as a result of chlorine transport based on mitigated case are drawn on the Figure 4.16. The highest risk level is 10^{-7} or 1 chance of fatality in 10^{7} per year. The lowest risk level is 10^{-9} or 1 chance of fatality in 10^{9} per year. As a matter of fact, both highest risk levels in mitigated case and base case are less than acceptable highest risk level of 10^{-6} per year, therefore, the individual risk in Changhwa corridor is acceptable. In mitigated case, the downwind distance of highest risk level is apparently smaller than the downwind distance of highest risk level in base case. Apparently, the target of risk reduction has been completed since safety improvement program had been run efficiently in Company C during 1996~2003.



Audit No: 1621528
Factors: Combination 1
Run Row Selected: 1
Study Folder: Chunghv

Figure 4.15 The individual risk contours in Changhwa corridor for the base case

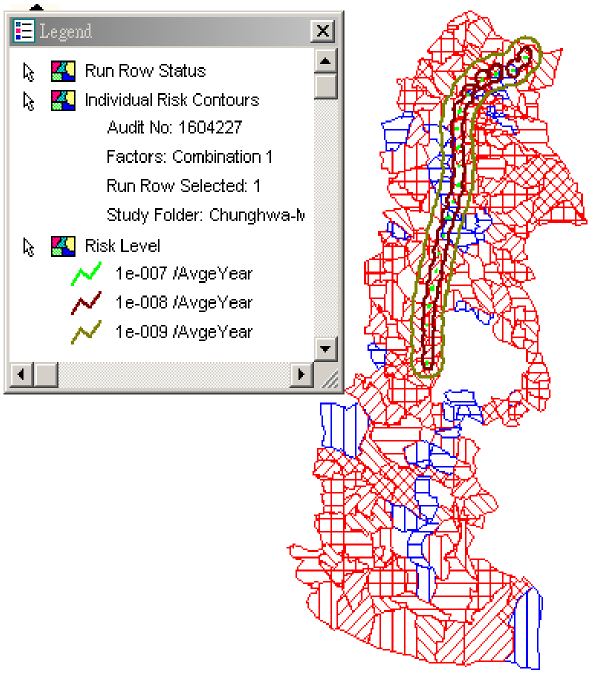


Figure 4.16 The individual risk contours in Changhwa corridor for the mitigated case.

4.1.9 Hsinchu Corridor Societal Risk, F-N Curve

The F-N curve for the base case is shown in Figure 4.17, the F-N curve for the mitigated case is shown in Figure 4.18. The F-N curves of Figure 4.17 and Figure 4.18 present overall risk that each risk of 1 (KM) segment is combined and accumulated through total length of evaluated corridor. Obviously, through Company C’s effort in continuously conducting safety improvement program during 1996~2003, risk reduction is apparent for transport in Hsinchu corridor. Detailed resulted F-N data comparison of base case versus mitigated case in Hsinchu corridor is outlined in Table 4.5. It must be emphasized that the F-N resulted curve of transport risk of Base case and mitigated case in Hsinchu corridor are within the As Low As Reasonably Practical (ALARP) range for Hong Kong risk criteria up to a fatality level of 1,000 or more fatalities. The societal risk associated with the chlorine transport in Hsinchu corridor is within acceptable levels. But for the “ALARP” concept that the risk must be reduced as could as possible in order to let F-N curve below Hong Kong risk criteria, continuous risk improvement is necessary to approach Hong Kong risk criteria.

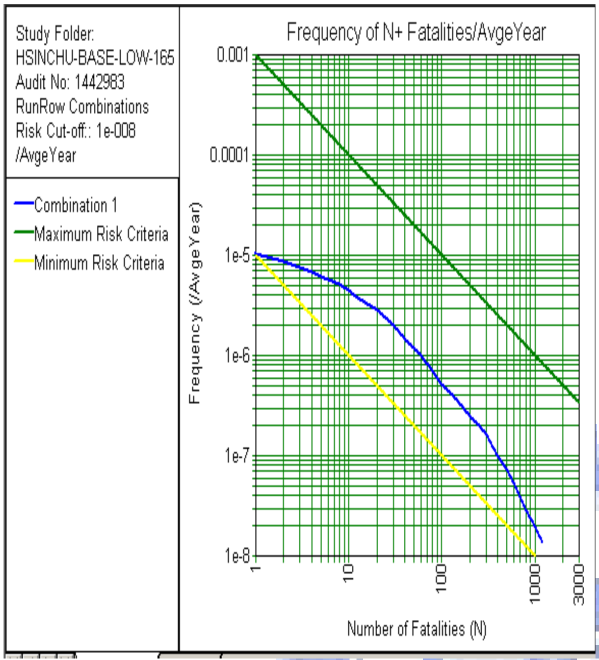


Figure 4.17 F-N curve for chlorine transport in Hsinchu corridor for the base case

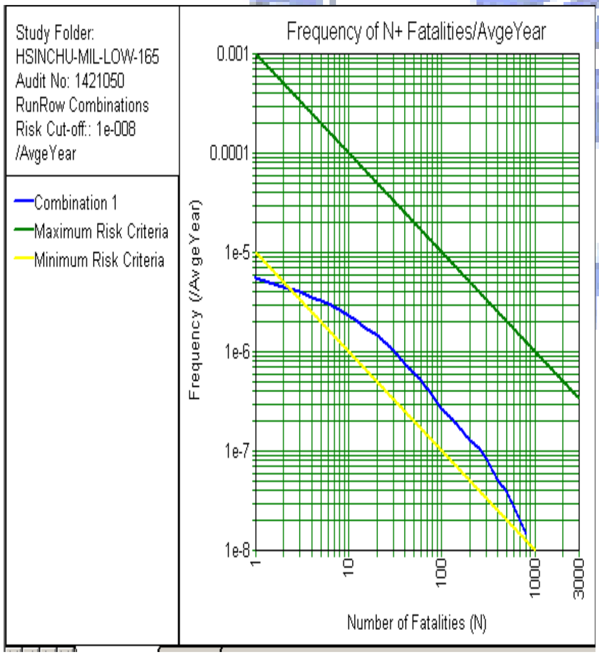


Figure 4.18 F-N curve for chlorine transport in Hsinchu corridor for the mitigated case

	Cumulative frequency of fatalities equal to and above N per year ($\times 10^6$)			
	N=1	N=10	N=100	N=1,000
Base Case	10	4.5	0.5	0.02
Mitigated Case	6	2.2	0.3	0

Table 4.5 F-N data comparison of base case versus mitigated case in Hsinchu corridor

4.1.10 Hsinchu Corridor Individual Risk

The likelihood of fatality for a hypothetical person who located at a specific point is visualized by individual risk contours. Certainly, the geographic representation of risk contour allows for the estimation of risk to who stays in specific work place, schools, and other denser population locations. The individual risk contours for the area surround Hsinchu corridor as a result of chlorine transport based on base case are drawn on the Figure 4.19 the highest risk level is 10^{-7} or 1 chance of fatality in 10^7 per year. The lowest risk level is 10^{-9} or 1 chance of fatality in 10^9 per year. The shape of these contours is primarily dependent on the local wind pattern in the area; the individual risk contours for the area surround Hsinchu corridor as a result of chlorine transport based on mitigated case are drawn on the Figure 4.20. The highest risk level is 10^{-7} or 1 chance of fatality in 10^7 per year. The lowest risk level is 10^{-9} or 1 chance of fatality in 10^9 per year. As a matter of fact, both highest risk levels in mitigated case and base case are less than acceptable highest risk level of 10^{-6} per year, therefore, the individual risk in Hsinchu corridor is acceptable. In mitigated case, the downwind distance of highest risk level is apparently smaller than the downwind distance of highest risk level in base case. Apparently, the target of risk reduction has been completed since safety improvement program had been run efficiently in Company C during 1996~2003.

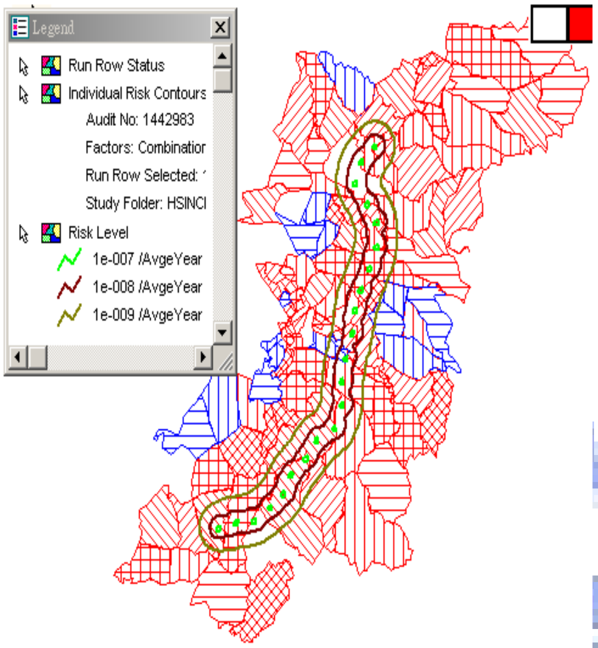


Figure 4.19 The individual risk contours in Hsinchu corridor for the base case

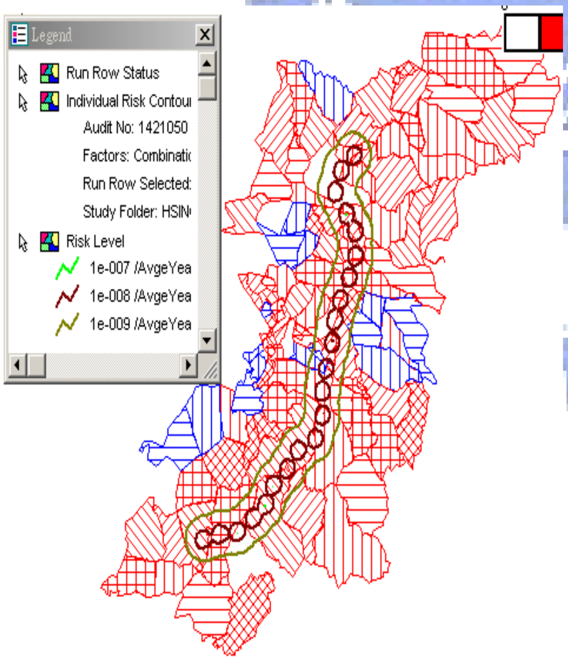


Figure 4.20 The individual risk contours in Hsinchu corridor for the mitigated case

4.1.11 Kaohsiung Corridor Societal Risk for Future Chlorine Trip Increment

In order to get better understanding on the risk increment for Company A’s business expansion with additional chlorine trips, the additional risk assessment from Kaohsiung corridor is reviewed. The same release scenario datasheet is applied except the change of trips from 996 to 1,378. The highest risk level of risk contour is 10^{-7} or 1 chance of fatality in 10^{8} per year. The lowest risk level of risk contour is 10^{-9} or 1 chance of fatality in 10^{9} per year. Highest risk levels of risk contour in future probable production capacity demand is less than acceptable highest risk level of 10^{-6} per year, but the high individual risk in future probable production capacity demand is 10 times higher than highest risk level in current production capacity mode, see Figure 4.21 for F-N curve, Figure 4.22 for individual risk.

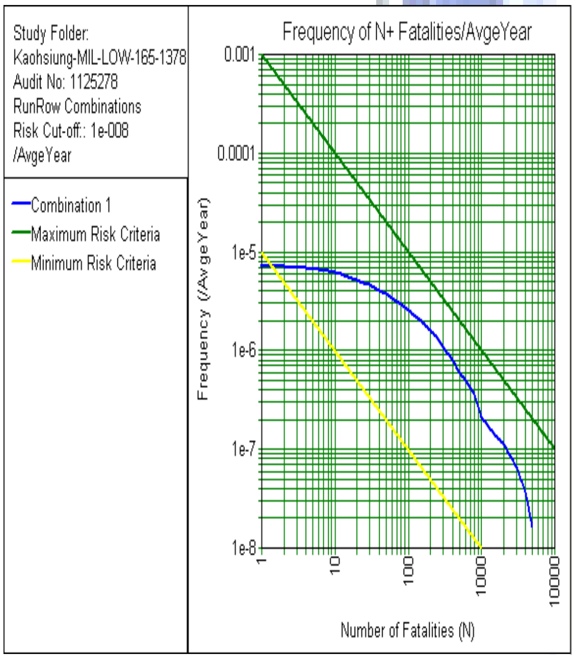


Figure 4.21 F-N curve for Kaohsiung corridor for future trip increment

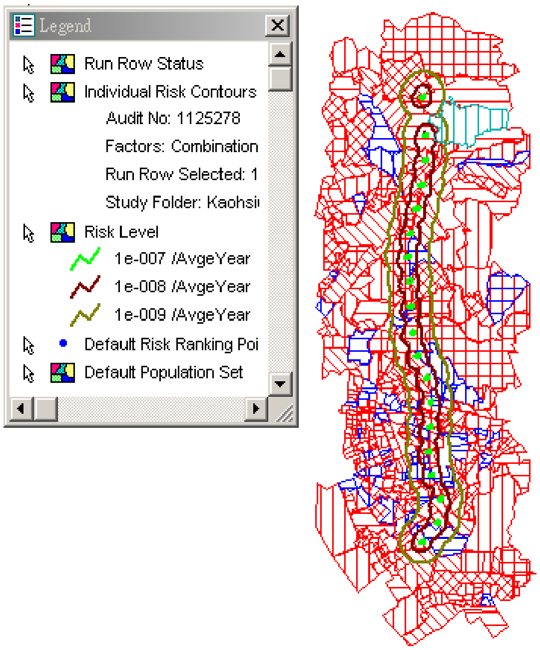


Figure 4.22 Risk contours for Kaohsiung corridor for future trip increment

4.1.12 Risk Comparison of Alternative Route versus Current Route

From the view of point of risk reduction, even though the risk of current mode of operation is within Hong Kong risk acceptable criteria, continuous safety improvement is necessary to approach and fit Hong Kong risk acceptable criteria. As for chlorine transport from COMPANY B to COMPANY A, the risk results in this project for all evaluated corridors which has higher risk are within Hong Kong risk acceptable criteria. Forward, in order to reach more efficient risk reduction, alternative route selection is preferred, it means that part of segments for transport route are substituted for other segments which present lower risk.

4.1.13 Alternative Route Evaluation in Northern Section

If Chungli corridor is not included in this transport route, in the other words, Expressway Number 66 local road provides passage to COMPANY A after chlorine truck pass Hsinchu corridor, the potential risk for bypassing Chungli corridor will be focused on Hsinchu corridor. Therefore, the representative risk for alternative route in northern section is presented based on Hsinchu corridor. Table 4.6 indicates that the risk of 1000 or more fatalities is very minor and can be neglected for alternative route. When risk of alternative route is compared with current route, risk resulting in 10 or more fatalities is 1.6 times less likely to occur, risk resulting in 100 or more fatalities is 1.3 times less likely to occur. A two-dimensional representation of risk known as an F-N curve is used in this study. F-N curves are used to plot the likelihood (or frequency-F) of exceeding a given consequence level (N-fatalities). The curves indicate how frequently an accident is expected to occur which exceeds 1 fatality, 10 fatalities, 100 fatalities, see Table 4.7.

	Cumulative frequency of fatalities equal to and above N per year ($\times 10^6$)			
	N=1	N=10	N=100	N=1,000
Current route	6	3.5	0.4	0.018
Alter- route	6	2.2	0.3	0

Table 4.6 F-N data comparison of alternative route versus current route in northern section

	Cumulative frequency of fatalities equal to and above N per year ($\times 10^6$)			
	N=1	N=10	N=100	N=1,000
Current operation mode	5	4	2	0.16
Future operation mode	7	6	2.5	0.2

Table 4.7 F-N data comparison of mitigated cases in Kaohsiung corridor - for current operation mode and future operation mode

4.1.14 Alternative Route Evaluation in Middle Section

If Taichung corridor is not included in this transport route, in the other words, Taichung corridor in Expressway Number 1 is substituted for middle segments of the Third Expressway that connected to

Hsinchu corridor in Expressway Number 1, the potential risk reduction is obvious for bypassing Taichung corridor since population density and accident rate records are lower for area surround Expressway Number 2 than Expressway Number 1. Therefore, this alternative route selection is feasible and can be realized.

4.2 Application of Six Sigma Methodology

Six Sigma Methodology and process is applied to examine the societal risk level from quantitative risk assessment to identify the critical parameters which would impact to the risk level of chlorine trip increments while business expansion. It also examines the effectiveness of improvements on risk reductions of critical factors. The Six Sigma methodology and process include 5 phases, which are "define", "measure", "analyze", "improve", and "control". In "define" phase, primary metrics, baseline performance metrics, and target performance need to be set. Actual improvements on risk reductions and their potential secondary metrics need to be monitored**.** Upper specification limit of risk data distribution shall be set to estimate initial six sigma and final (target) sigma values. Appropriate approaches and tools in Minitab 14 statistical software is used to determine these parameters. In "measure" phase, the SIPOC process map needs to be developed, which includes "Supplier", "Input", "Process", "Output", and "Customer". Data collection plan shall be developed to collect appropriate data. The risk function equation shall be developed. Function Y = f(Xi), i =1 to n. Y represents the number of F(Frequency) times N(Number of Fatalities under F value in F-N Curve). Xi ~ Xn represent the critical actors that would impact Y. In "analyze' phase, chi-square, χ^2 testing method, and Pareto Chart are applied to identify the critical X's. In "improve" phase, action plan is developed to improve the critical X's. In "control" phase, control plan is developed to maintain the gain. Minitab 14 software, the statistical software developed from Six Sigma Academy was applied to this thesis

4.2.1 Primary Metrics

A typical representation of quantitative risk assessment (QRA) is an F-N curve, where F represents cumulative frequency for an accident resulting in more than N fatalities. The primary metrics for this project are defined as F×N products on sampling points of F-N curves for a given transport route (corridor). Risk coefficient is roughly a summation of those F-values (actually, an integral) and can be viewed as an expected value of total fatalities in a release event resulted from a traffic accident of a truck filled with liquid chlorine.

4.2.2 Baseline Performance

In 2003, 996 trucks carried liquid chlorine from COMPANY B in Kaohsiung to COMPANY A Company A Plant through the route of Kaohsiung-Taichung-Chungli. With accident rate of 0.078 per million kilometers, provided by contracted transport Company C, and truck volume of 16.5 tones, the baseline risk coefficient is calculated as 1.832×10^{-4}.

4.2.3 Target Performance

Target performance for this project is to reduce by 30% the risk coefficient of chlorine transport in the long term, with annual chlorine demand reaching 21,600 tones.

4.2.4 Actual Improvement

The risk coefficient can be reduced to 1.148×10^{-4}, or 37.34% reduction, with the improvement actions listed below (for an annual chlorine demand of 21,600 tones).

1. Accident rate to be reduced to 0.039 per million kilometers, or half the level in 2003. We need to push COMPANY B to put continuous efforts on reducing accident rate of Chlorine trucks.
2. Route to be changed to the Kaohsiung-Changhwa-Hsinchu corridors to take advantage of lower fatality risk in rural areas. Currently the route has been changed from Kaohsiung-Taichung-Chungli to Kaohsiung-Taichung-Hsinchu. We need to push COMPANY B to get approval on the new route.
3. Larger truck volume (18.0 MT) can reduce truck trips under the same annual transport amount of Chlorine. The difference in trips, however, is not big enough to show difference in transport risk. Therefore, in terms of transport risk, it is not necessary to try to load more liquid Chlorine into current 16.5 MT Chlorine truck.

4.2.5 Secondary Metric

One key secondary metric for this project is operation feasibility. There are many meaningful ways to reduce Chlorine transport risk but we have to judge by operation experience and statistical tools for operationally feasible ones.

4.2.6 Initial/Final Sigma Values

Sampling from F-N curves of three corridors, we got a number of F×N products. Hong Kong criteria for fixed facilities risk ($F \times N = 10^{-3}$) was applied as borderline between “unacceptable” and “ALARP” (As Low As Reasonably Practicable), and also as USL. Conditions for initial and final scenarios, including sigma values, are shown in the Table 4.8 and Table 4.9.

Annual Trips	996	1,310
Truck Volume	16.5 MT	16.5 MT
Accident Rate	0.078 (per 10^6 km)	0.039 (per 10^6 km)
Truck Route	Kaohsiung -Taichung-Chungli	Kaohsiung-Changhwa-Hsinchu
Risk Coefficient	1.832×10^{-4}	1.148×10^{-4}

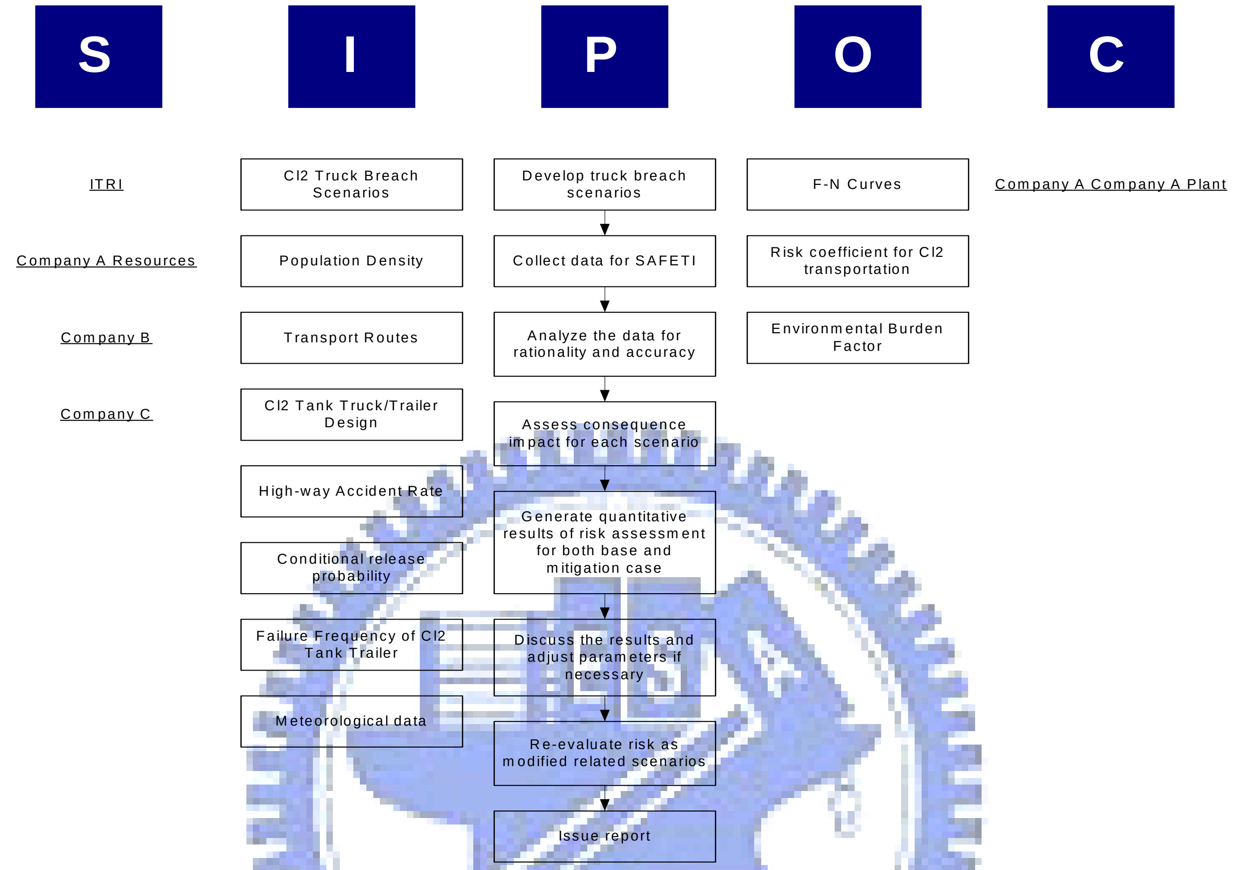
Table 4.8 Parameters with different annual trip numbers

	Initial	Final
Sigma Values	5.40	7.13
Year	2003	2009

Table 4.9 Initial (before improvement) and Final(after improvement) Sigma Values of F-N curves by setting USL, upper spec limit($F \times N = 10^{-3}$) at the unacceptable level of Hong Kong Criteria.

4.2.7 Define/Measure

Define phase included charter and process map/SIPOC (Supplier, Input, Process, Output, and Customer), see Table 4.10.



S	I	P	O	C
ITRI	Cl2 Truck Breach Scenarios	Develop truck breach scenarios	F-N Curves	Company A Company A Plant
Company A Resources	Population Density	Collect data for SAFETI	Risk coefficient for Cl2 transportation	
Company B	Transport Routes	Analyze the data for rationality and accuracy	Environmental Burden Factor	
Company C	Cl2 Tank Truck/Trailer Design	Assess consequence impact for each scenario		
	High-way Accident Rate	Generate quantitative results of risk assessment for both base and mitigation case		
	Conditional release probability	Discuss the results and adjust parameters if necessary		
	Failure Frequency of Cl2 Tank Trailer	Re-evaluate risk as modified related scenarios		
	Meteorological data	Issue report		

Table 4.10 SIPOC(Supplier, Input, Process, Output, Customer) Diagram

For calculations of SAFETI, the quantitative risk assessing software, scenarios were developed, corridors were selected, and data for calculation were collected per data-collection plan, including –

1. Transport routes (corridors)
2. Corridor population density along Chlorine truck routes
3. Historical Company C accident rate of Chlorine truck
4. Historical Chlorine truck trips per year
5. Truck capacity
6. Truck tank failure rate
7. Truck inner temperature and pressure
8. Chlorine toxic properties
9. Meteorological Data
   (1) Weather stability
   (2) Wind directions

(3) Wind speeds

(4) Sunshine hours in a day

(5) Cloudiness

Year 2003 was selected as baseline case – 996 trucks (assume all of 16.5 MT), Company C accident rate 0.078 accidents per million kilometers, and Kaohsiung-Taichung-Chungli as corridors on Chlorine truck route. It is calculated the F-N curves for the three corridors as below examples.

Refer to Figure 4.23, Figure 4.24, and Figure 4.25, the tilt green line represents Fixed Facilities Risk Criteria of Hong Kong, or F×N = 10^{-3}, the tilt yellow line represents F×N = 10^{-5}, and F represents cumulative frequency for an accident resulting in more than N fatalities. ALARP stands for “As Low As Reasonably Practicable”.

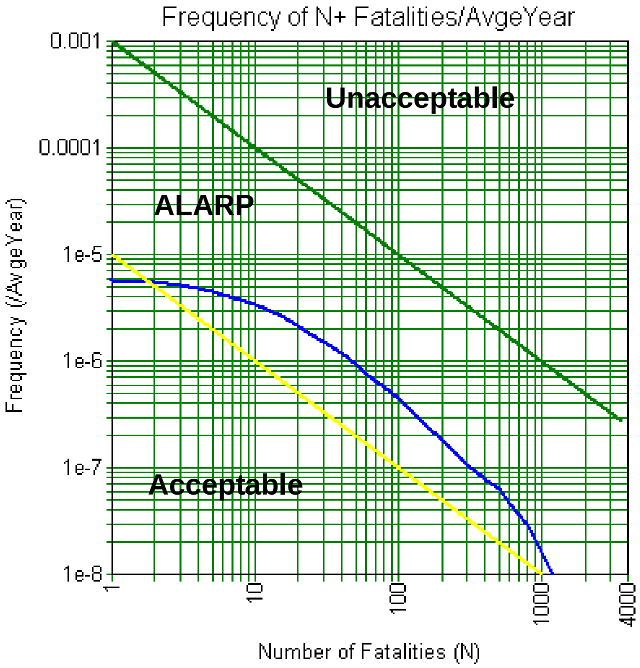


Figure 4.23 Kaohsiung Corridor F-N curve for the base case

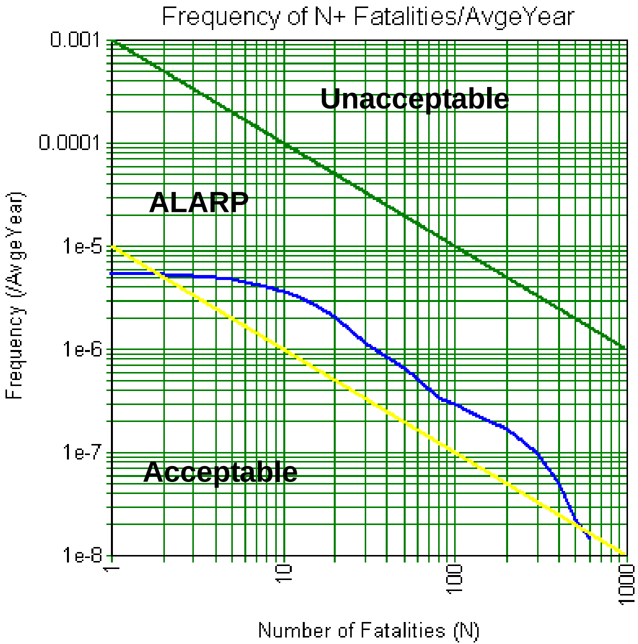


Figure 4.24 Taichung Corridor F-N curve for the base case.

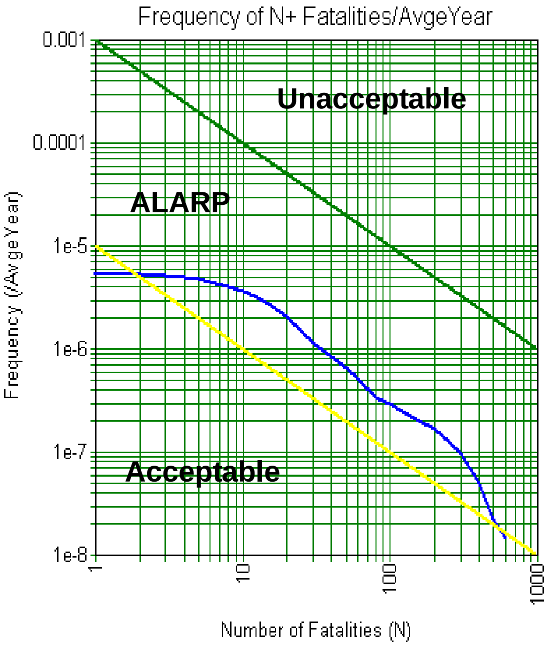


Figure 4.25 Chungli Corridor F-N curve for the base case

Y was selected as F-N products. Sampling from the F-N curves shown in Figure 4.23, Figure 4.24 and Figure 4.25, the distribution is not normal, see Figure 4.26. With the upper spec limit set at 10^{-3}, the process capability analysis (initial Six Sigma value) for this non-normal distribution is 5.40, see Figure 4.27.

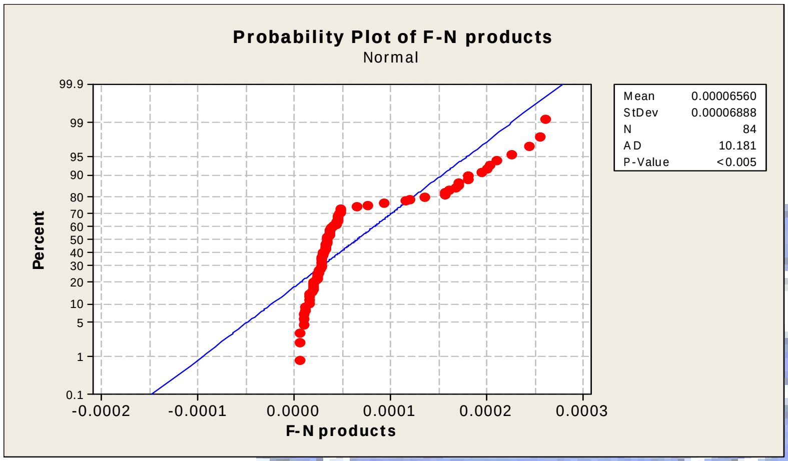


Figure 4.26 Normality test for FxN data points from Figure 4.23, 4.24, and 4.25.

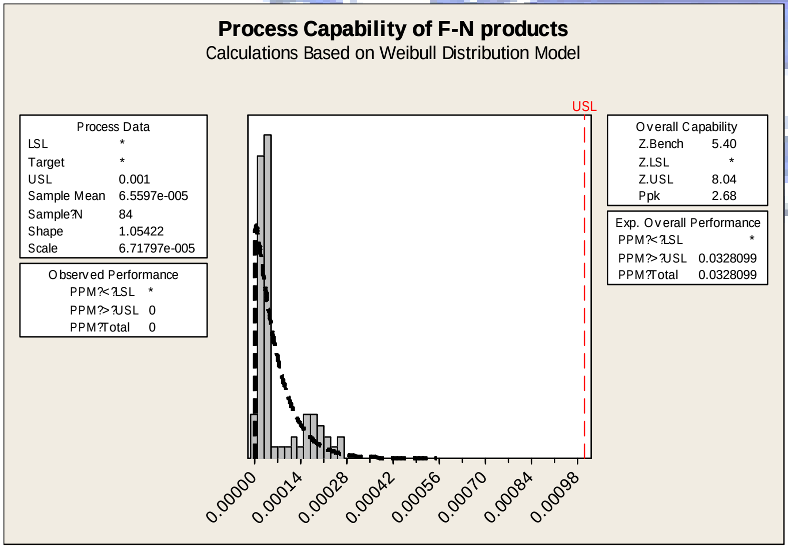


Figure 4.27 With USL = 10^{-3}, initial sigma value of FxN data points was calculated 5.40, using non-normal model.

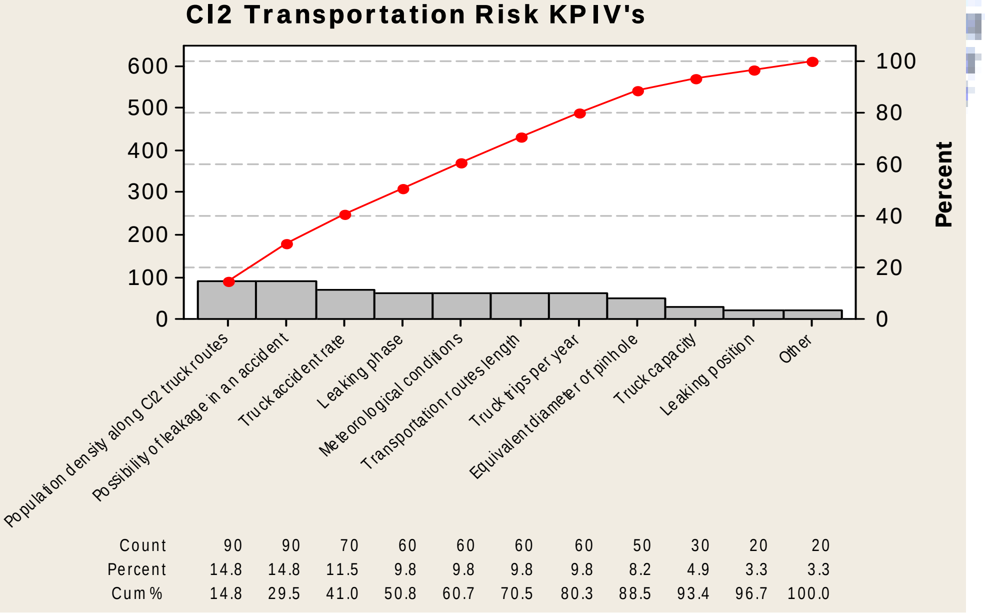
4.2.8 Analyze

Several factors affecting the level of road Chlorine transport risk were listed. Those factors were prioritized by rating and listed in a Pareto chart as shown in Figure 4.28.

The critical factors below contribute 80% weighting in the Pareto Chart

1. Population density in the neighborhood along Chlorine truck routes
2. Possibility of leakage in an accident
3. Truck accident rate
4. Meteorological conditions
5. Transport routes
6. Truck trips per year
7. Leaking phase

We cannot control or change items 1), 2), 4), 7). Therefore, truck accident rate, transport routes and truck trips per year are critical Xs for Y.



Count	90	90	70	60	60	60	60	50	30	20	20
Percent	14.8	14.8	11.5	9.8	9.8	9.8	9.8	8.2	4.9	3.3	3.3
Cum %	14.8	29.5	41.0	50.8	60.7	70.5	80.3	88.5	93.4	96.7	100.0

Figure 4.28 Pareto chart for chlorine transport risk KPIV's, Key Performance Impact Variables.

4.2.8.1 Truck Accident Rate

The simulated baseline case and worse case conditions are shown in the Table 4.11. The only difference is accident rate.

Since the distribution of Y (F-N products) is non-normal, those distributions were thus viewed as discrete data and χ^2-test was used to compare the two cases. The two distributions were divided into several sub-groups, as shown in the Table 4.12.

χ^2-test shows those two distributions are inconsistent. Accident rate is a critical X, see Table 4.13 for the χ^2-test.

Cases	Baseline	Worse
Annual Trips	996	996
Truck Volume	16.5 MT	16.5 MT
Routes	Kaohsiung-Taichung-Chungli	Kaohsiung-Taichung-Chungli
Accident Rate	0.078 per 10^6 km	0.159 per 10^6 km

Table 4.11 Truck accident rates for baseline and worse cases

Interval	Counts (Baseline)	Counts (Worse)
$10^{-3.5} \sim 10^{-3.0}$	0	14
$10^{-4.0} \sim 10^{-3.5}$	19	8
$10^{-4.5} \sim 10^{-4.0}$	30	50
$10^{-5.0} \sim 10^{-4.5}$	31	12
$10^{-5.5} \sim 10^{-5.0}$	4	0

Table 4.12 Two data points distributions of baseline and worse cases at different intervals.

Table 4.13 Chi-Square test for baseline and worse cases

Chi-Square Test: Baseline, Worse(by using Minitab)

```
        Baseline   Worse   Total
1           0        14      14
         7.00      7.00
        7.000     7.000

2          19         8      27
        13.50     13.50
        2.241     2.241

3          30        50      80
        40.00     40.00
        2.500     2.500

4          31        12      43
       21.50     21.50
        4.198     4.198

5           4         0       4
        2.00      2.00
        2.00      2.00

Total    84        84      168
```

Chi-Sq = 35.877, DF = 4, **P-Value = 0.000**

4.2.8.2 Transport Routes

The simulated baseline case and new-route case conditions are shown per Table 4.14. The only difference is route.

The two distributions were divided into several sub-groups, as shown in the Table 4.15.

χ^2-test shows those two distributions are consistent. Routes do not significantly influence transport risk, see Table 4.16 for the χ^2-test.

Cases	Baseline	New Route
Annual Trips	996	996
Truck Volume	16.5 MT	16.5 MT
Routes	Kaohsiung-Taichung-Chungli	Kaohsiung-Taichung-Hsinchu
Accident Rate	0.078 per 10^6 km	0.078 per 10^6 km

Table 4.14 Truck accident rates for baseline and new route cases.

Interval	Counts (Baseline)	Counts (New Route)
$10^{-4.0} \sim 10^{-3.5}$	19	19
$10^{-4.5} \sim 10^{-4.0}$	30	15
$10^{-5.0} \sim 10^{-4.5}$	31	43
$10^{-5.5} \sim 10^{-5.0}$	4	5

Table 4.15 Two data points distributions for baseline and new route cases at different intervals

Table 4.16 Chi-Square Test for Baseline and Worse cases

Chi-Square Test: Baseline, New Route(by using Minitab)

```
     Baseline  New Route  Total
  1        19         19     38
       19.23      18.77
       0.003      0.003

  2        30         15     45
       22.77      22.23
       2.295      2.351

  3        31         43     74
       37.45      36.55
       1.110      1.137
```

```
    4          4          5      9
            4.55       4.45
           0.067      0.069

Total         84         82    166

Chi-Sq = 7.034, DF = 3, P-Value = 0.071
```

4.2.8.3 Truck Trip

The simulated cases of less and more trucks conditions are shown as Table 4.17. The only difference is annual trip of Chlorine truck.

The two distributions were divided into several sub-groups, as shown in Table 4.18.

χ^2-test shows those two distributions are inconsistent. Truck Trip is a critical X for Chlorine transport risk, see Table 4.19 for the χ^2-test.

Cases	Less Trucks	More Trucks
Annual Trips	996	1310
Truck Volume	16.5 MT	16.5 MT
Routes	Kaohsiung-Changhwa-Hsinchu	Kaohsiung-Changhwa-Hsinchu
Accident Rate	0.078 per 10^6 km	0.078 per 10^6 km

Table 4.17 Truck accident rates for “fewer trucks” and “more trucks” cases

Interval	Counts (Less Trucks)	Counts (More Trucks)
$10^{-4.0} \sim 10^{-3.5}$	19	22
$10^{-4.5} \sim 10^{-4.0}$	24	40
$10^{-5.0} \sim 10^{-4.5}$	39	23
$10^{-5.5} \sim 10^{-5.0}$	4	3

Table 4.18 Two data points distributions for less trucks and more trucks at different intervals

Table 4.19 Chi-Square Test for “less trucks” and “more trucks” cases

Chi-Square Test: Less, More Trucks(by using Minitab)

```
          Less    More   Total
    1       19      22      41
         20.26   20.74
         0.079   0.077

    2       24      40      64
         31.63   32.37
         1.841   1.800

    3       39      23      62
         30.64   31.36
         2.279   2.227

    4        4       3       7
          3.46    3.54
         0.084   0.082

Total       86      88     174


Chi-Sq = 8.470, DF = 3, P-Value = 0.037
```

4.2.8.4 Truck Volume

Another factor that affects truck trips is truck volume. The larger the truck volume, the less truck trips in a year, under the same annual transport amount of Chlorine. Below table summarizes the conditions for simulation taking future demand as basis, see Table 4.20.

The two distributions were divided into several sub-groups, as shown in Table 4.21.

χ^2-test shows those two distributions are consistent. Truck Volume does not have significant influence on Chlorine transport risk, see Table 4.22 for the χ^2-test.

Cases	Current Truck Volume	Larger Truck Volume
Annual Trips	1,310	1,200
Truck Volume	16.5 MT	18.0 MT
Routes	Kaohsiung-Changhwa-Hsinchu	Kaohsiung-Changhwa-Hsinchu
Accident Rate	0.078 per 10^6 km	0.078 per 10^6 km

Table 4.20 Truck accident rates for “current truck volume” and “larger truck volume” cases.

Interval	Counts (16.5 MT)	Counts (18.0 MT)
$10^{-3.75} \sim 10^{-3.50}$	16	22
$10^{-4.00} \sim 10^{-3.75}$	6	5
$10^{-4.25} \sim 10^{-4.00}$	10	10
$10^{-4.50} \sim 10^{-4.25}$	30	30
$10^{-4.75} \sim 10^{-4.50}$	16	16
$10^{-5.00} \sim 10^{-4.75}$	7	8
$10^{-5.25} \sim 10^{-5.00}$	3	3

Table 4.21 Two data points distributions for different truck volume cases at different intervals

Table 4.22 Chi-Square Test for “current truck volume” and “larger truck volume” cases

Chi-Square Test: 16.5 MT, 18.0 MT (by using Minitab)

Chi-Sq = 1.070, DF = 6, **P-Value = 0.983**

4.2.9 Improve

From analysis results, we identified two critical Xs for chlorine transport risk – accident rate and chlorine truck trip. As liquid chlorine demand goes up in the future, truck trip goes up as well. The way to reduce or maintain risk level in the future is to push COMPANY B/Company C to reduce accident rate of chlorine trucks.

In addition, transport route does not significantly affect transport risk level. This finding gives flexibility on routes selection subject to local regulations.

If, in the future, accident rate of chlorine truck can be reduced to 50% of current level, transport risk will be significantly reduced even though annual trips go from 996 to 1310 (21,600 tones of annual chlorine demand), see Table 4.23 and Table 4.24.

Taking the future case as final case, we can calculate final sigma value 7.13 based on a non-normal model with USL = 10^{-3}, see Figure 4.29.

Cases	Baseline	Future
Accident Rate	0.078 per 10^6 km	0.039 per 10^6 km
Truck volume	16.5 MT	16.5 MT
Annual Trips	996	1,310
Routes	Kaohsiung-Taichung-Chungli	Kaohsiung-Changhwa-Hsinchu
Interval	Counts	Counts
$10^{-3.75}$ ~ $10^{-3.50}$	10	0
$10^{-4.00}$ ~ $10^{-3.75}$	9	15
$10^{-4.25}$ ~ $10^{-4.00}$	3	5
$10^{-4.50}$ ~ $10^{-4.25}$	27	10
$10^{-4.75}$ ~ $10^{-4.50}$	23	28
$10^{-5.00}$ ~ $10^{-4.75}$	8	15
$10^{-5.25}$ ~ $10^{-5.00}$	2	7
$10^{-5.50}$ ~ $10^{-5.25}$	2	3

Table 4.23 Two data points distributions for baseline and future cases at different intervals.

Table 4.24 Chi-Square Test for baseline and future cases at different intervals

Chi-Square Test: Baseline, Future

Chi-Sq = 25.404, DF = 7, **P-Value = 0.001**

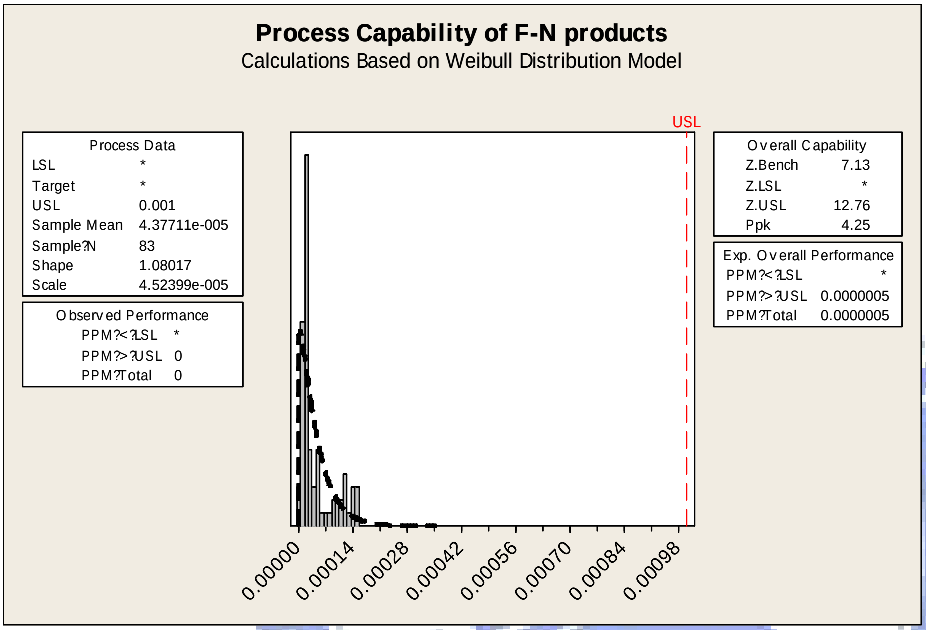


Figure 4.29 With USL = 10^{-3}, final sigma value of FxN data points was calculated 7.13, using non-normal model

4.2.10 Control

A control plan needs to be developed for the goal of reducing/maintaining transport risk level in future capacity expansion of Company A Plant.

It will not impact negatively on transport risk to select a different transport route. The selection should be subject to –

1. Local regulations
2. Routes through less populated areas
3. Easy to access when Chlorine truck gets trouble on the way

Chapter 5 Conclusions and Recommendations

Though the Six Sigma methodology and Quantitative Risk Assessment already indicated several key factors that would contribute to the overall risk, some qualitative countermeasures need to take into considerations for further risk reductions as follows:

1. Replace the Chungli corridor with the Expressway Number 66 in the transport route, in the other words, the Expressway Number 66 provides passage to Company A after the chlorine truck passes the Hsinchu corridor.
2. Bypass the Taichung area by using Expressway Number 2 to connect with the Expressway Number 3, which will connect back to the Expressway Number 1 in the area of the Hsinchu corridor.
3. Trip number is a significant factor in the societal risk of chlorine transport. In order to reduce the number of trips, 16.5 MT chlorine trucks are available for transporting the chlorine. To determine the impact on risk of using larger capacity trucks (fewer trips but potentially greater consequences), it is recommended the risk be re-evaluated using the assumption of fewer trips with larger capacity trucks.
4. The Company C should continuously improve its safety management program, especially focused on reduction of the accident rate.

Since the primary contributor to risk is from the Kaohsiung corridor, Company C should consider if speed reductions are possible. Continued cautious and defensive driving behavior by the chlorine drivers will help in the prevention of accidents.

From Six Sigma Methodology, there is some key learning:

1. Chlorine Truck accident rate and Chlorine truck trips are critical to chlorine transport risk.
2. Route selection is flexible but subject to local regulations.
3. Future transport risk, even though chlorine truck trips increase as Company A capacity increases, can be reduced if COMPANY B/Company C continues putting efforts on reducing chlorine truck accident rates.

The author of thesis also interviewed several benchmarking local chlorine carriers, suppliers, and consumers who participated in the thesis study, and have highlighted some key success factors for chlorine transport risk management, other than the QRA has identified.

The key success factors other than QRA include:

1. Cope with International safety, health, and environmental standards: Launch international standards, for example ISO 9002, ISO 14001, and OSHAS 18001. This is to ensure that carriers

or suppliers to have a more comprehensive management system that can maintain a high level of sensitivity on their safety, health and environmental performance.

2. Upgrade vehicle’s safety devices and integrity: Follow ‘European Agreement of Dangerous Goods Transport on Road’ and facilitate auto explosive equipments and shock absorbers. Regular check before outgoing, during loading, unloading, transporting, and rest are made. Preventive maintenance is scheduled at a routine basis. Maintain designated materials tanks and Parking areas. Placed two large brake flash lights of each chlorine tanks and equip ABS (Anti-Brake System) and stabilizer for all tractors and trailers. Develop the tire pressure and overheat monitoring system for driving and control center. Replace all the tires with tubeless tires to prevent tire blowout, and enlarge the brake alert lights on the rear to have clearer indicators. Angle valves and the outlet threads should be replaced or rebuilt every 50 trips by following US Chlorine Institute requirements. Replace the aged trailers with more restricted code (US DOT MC331 code) of new trailers, and equipped with thicker jacket for the insulation to provide more protections from puncture accidents.
3. Conduct driver performance assessment: ADR is installed at each truck. Designated route should be requested to provide the drivers good sense of route conditions. Behaviors and attitude should be evaluated by appropriate employee evaluation program. Good employee training and health care program should be used.
4. Continuously upgrade the vice driver system: Need to develop the vice driver system with wireless GPRS (Global Positioning Recording System) and two way communication. CCD (Camera Capturing Display) technology can be used to capture pictures and then transmit back to the control center. Use CCD to capture the pictures and analyze at real time to alarm the drivers for their inappropriate driving behaviors.
5. Develop Emergency Response System and Competency: Set up 24 hours control center and emergency response team. Emergency response plan should be developed and in place. Sufficient fixed emergency response control centers should be established. Standard operating procedures should be developed for managing any possible leaks during transport. Quarterly refresher training for drivers should be provided to maintain high confidence level of emergency response capability. More Involvement in emergency response symposiums sponsored by local Fire Marshals, Environmental Bureaus, Industrial Development Bureau, and ERIC (Emergency Response Information Center) to build more mature mutual aid alliance.
6. Enhance Process Safety Management through Responsible Care: PSM (Process Safety Management) diligence and competency shall be built and enhanced. They include Personal

Training and Performance, Auditing, Contractor Safety Management, Incident Reporting and Investigation, Emergency Response, Management of Change – Personnel/Subtle/Technology, Mechanical Integrity, Quality Insurance, Process Hazard Analysis, Pre-start up Safety Reviews, Process Technology, and Operating Procedures and Safe Work Practices.

7. Upgrade the security controls: The chlorine operations sites or carriers need to conduct a thorough security vulnerability assessment with four phases(“Deter”, “Detect”, “Delay”, and “Respond”) and the following seven steps
   (1) Formation of a Multi-disciplined Team
   (2) Facility Characterization
   (3) Threat Assessment
   (4) Vulnerability Analysis
   (5) Development of Countermeasures
   (6) Implementation of Risk Reduction Program
   (7) Documentation of Findings/Implementation

Implementation Guide for Responsible Care® Security Code of Management Practices Site Security & Verification [18], issued by American Chemistry Council on July 2002 will be a good reference for implementation.

References

1. M.J. Borysiewicz, Transport Risk Assessment, CoE MANHAZ, Institute of Atomic Energy, pp 13-14.
2. H. Knoflacher, P. C. Pfaffenbichler, H. Nussbaumer, Quantitative Risk Assessment of Heavy Goods Vehicle Transport through Tunnels – the Tauerntunnel Case Study, pp 2-3.
3. Ghada Mahmoud Hamouda, Risk-Based Decision Support Model for Planning Emergency Response for Hazardous Materials Road Accidents, pp 31-32.
4. Center for Chemical Process Safety, American Institute of Chemical Engineers. "Guidelines for Chemical Process Quantitative Risk Assessment", New York, New York, 1989. pp 395-403, pp 579-605.
5. Michel Nicolet-Monnier and Adrian V. Gheorghe, "Quantitative Risk Assessment of Hazardous Materials Transport Systems", Kluwer Academic Publishers, pp 2-18.
6. William R. Rhyne, "Hazardout Materials Transport Risk Analysis – Quantitative Approaches for Truck and Train", Van Nostrand Reinhold, pp 3-10.
7. Quentin Brook, " Six Sigma and MINITAB – A Toolbox Guide for Managers, Black Belts and Green Belts", QSB Consulting.
8. C.A. Geffen, "An Assessment of the risk of Transporting Propane by Truck and Train", March 1980.
9. Minitab Release 14, Statistical Software.
10. Mikel J. Harry, Ph.D., "The Vision of Six Sigma: Tools and Methods for Breakthrough", Tri Star Publishing, v1-v3.
11. J. Anthony and R. Banuelas, "Key ingredients for the effective implementation of Six Sigma program", Measuring Business Excellence, 6, 4, 2002, pp 20-27.
12. ICF Consulting, "Risk Management Framework for Hazardous Materials Transport", submitted to the US Department of Transport Research and Special Programs Administration, November 1, 2000.
13. N.J. Scenna and A.S.M. Santa Cruz, "Road risk analysis due to the transport of chlorine in Rosario city", Reliability Engineering & System Safety, 90, 1, 2005, pp 83-90.
14. B. Fabiano, F. Curro, A.P. Reverberi and R. Pastorino, "Dangerous good transport by road: from risk analysis to emergency planning", J of Loss Prevention in the Process Industries, 16, 4-6, 2005, pp 403-413.
15. P. Cassini, "Road transport of dangerous goods: quantitative risk assessment and route comparison", J of Hazardous Materials, 61, 1-3, 1998, pp 133-138.
16. R. Bubbico, S. Di Cave and B. Mazzarotta, "Risk analysis for road and rail transport of hazardous

materials: a simplified approach", J of Loss Prevention in the Process Industries, 17, 6, 2004, pp 477-482.

17. DNV Technica, "SAFETI(Suite for the Assessment of Flammable, Explosive and Toxic Incidents) software".

18. American Chemistry Council, Implementation Guide for Responsible Care® Security Code of Management Practices Site Security & Verification, July 2002.

自傳

學生鄭允豪，祖籍澎湖，民國五十六年出生於台南市，畢業於台南一中及成功大學化工系。

幼年失怙，家境小康，由母親撫養長大。上有一兄一姐，均已婚且育有子女。學生已婚，妻為公務員，服務於台北縣泰山國中。育有一對子女，分別為十歲(女)及八歲(男)。家庭生活美滿。

學生自憲兵退役後，先後服務於中鋼碳素化學公司及台灣杜邦公司，目前擔任杜邦公司特用化學品事業部亞太區產品安全管理經理等工作。並義務擔任經濟部及勞委會等相關政府部會工安諮詢工作。

閒暇之餘，學生喜愛從事閱讀、籃球、及戶外活動，並藉由修習氣功調養身心。

對於將來的生涯規劃，學生希望能再多回到校園，充實自己在工業安全衛生領域上的專業，讓自己可以更加自我肯定，並且更有專業能力，為公司及台灣的工業安全衛生貢獻更多心力。