QUANTITATIVE RISK ASSESSMENT OF HAZARDOUS MATERIALS DURING ROAD TRANSPORTATION WITH ACCIDENT CAUSATION MODELS

By

AJAYA KUMAR K

COLLEGE OF ENGINEERING STUDIES
(DEPARTMENT OF HEALTH, SAFETY & ENVIRONMENT)

Submitted

IN PARTIAL FULFILMENT OF THE REQUIREMENT OF THE DEGREE OF

DOCTOR OF PHILOSOPHY

TO

UNIVERSITY OF PETROLEUM AND ENERGY STUDIES

DEHRADUN
NOVEMBER, 2016

Under the Guidance of

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DEDICATION

This thesis is dedicated to my parents, wife and children,

who have always stood by me and dealt with all of my absence

from

many personal occasions

with a smile.

ACKNOWLEDGEMENTS

I express my sincere thanks to my thesis supervisors Dr. Nihal Anwar Siddiqui, Dr. Kanchan Deoli Bahukhandi and Dr. Ashutosh Gautam for their guidance, encouragement and support throughout my work.

I express my gratitude to all my friends and colleagues in College of Engineering, Thiruvananthapuram, Caledonian College of Engineering, Muscat, International College of Engineering and Management, Muscat and Amal Jyothi College of Engineering, Kanjirappally for their moral support and encouragement.

I am grateful to Dr. Srihari, Dr. Kamal Bansal, Dr. S. M. Tauseef and other senior faculty members in UPES for their critical reviews on my research work at various stages.

I express my thanks to Dr. Benny Joseph, Dr Ayoob Sulaiman and Mr. R. Tamilselvan for their constant support and motivation at various stages.

Even though it was on a condition of anonymity, I am grateful to the police officers in Kerala Police and Engineers in Kerala Public Works Department and National Highway Authority of India, who gave valuable information about the accidents and guided me to the sources of data. I express my sincere gratitude to my media friends for providing access to their library in finding out the details of the accidents and to proceed further. Also the doctors in the nearby hospitals of accidents spots, who treated the injured persons but mentioned the nature of accidents in their summary reports.

I thank all those who helped me in statistical analysis, programming, software support and on documentation techniques.

I appreciate Dr. P K Gupta, Dr. Anjali, Dr. Rakhi Mr. Abhilash Dubey, Mr. Vivek for their support in UPES administrative matters.

I am especially glad to my wife Ms. Asha, my daughters Ms. Bhagyathara and Ms. Bhavyajyothy and all my close family members for their co-operation, understanding and support during the course of my research.

Ajaya Kumar K
25 November 2016

DECLARATION BY THE AUTHOR

I hereby declare that this submission is my own work and and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

25.11.2016 AJAYA KUMAR K

THESIS COMPLETION CERTIFICATE

This is to certify that the thesis on **"Quantitative Risk Assessment of Hazardous Materials during Road Transportation with Accident Causation Models"** submitted by **Ajaya Kumar K** to University of Petroleum and Energy Studies in partial completion of the requirements for the award of the Degree of Doctor of Philosophy (Engineering) is an original work carried out by him under our joint supervision and guidance.

It is certified that the work has not been submitted anywhere else for the award of any other diploma or degree of this or any other University.

Internal Guide:

Dr. Nihal Anwar Siddiqui

Internal Co Guide:

Dr. Kanchan Deoli Bahukhandi

External Guide:

Dr. Ashutosh Gautam

CONTENTS

Quantitative Risk Assessment of Hazardous Materials during Road Transportation with Accident Causation Models

EXECUTIVE SUMMARY

Transport operations of hazardous materials have greater risks during the entire stretch of transportation. Even if low frequency and high impact incidents are reported, it has caused in significant human loss in the industry. Environmental damage also is very high. But, every accident is associated with different type of failures with different root causes. An analysis of the pattern of accidents and occurrence of incident with root causes can act proactively to prevent or to reduce loss or damages.

A number of incidents involving the release of toxic chemicals are reported leading to serious consequences during the transportation of Hazardous Materials. Most of the hazards can be eliminated or limited to a minimum through the use of risk analysis. A powerful tool like Transportation Risk Analysis can be used to select the most suitable alternative with a reduced risk.

The various risk components like frequency, risk scenario, risk consequence, and likelihood are to be properly mapped with the selected route to obtain the best output. But due to the changes in urbanization, the characteristics of the neighbourhood of selected route are changing, resulting in a serious consequence.

The attributes resulting in accidents can be related to the road, vehicle, user or environment. The initiating events of accidents, the outcomes of the incident, meteorological conditions, population, and time of occurrence, all have influence in determining the severity of accidents. A model incorporating the various causes of accidents and its effects on neighbourhood population during Hazardous Material transportation based on decision support system is not available. This research is an attempt to identify the scope for linking

Quantitative Risk Assessment of Hazardous Materials during road transportation with accident causation models, using the real incident data from Kerala.

The factors involved in the accidents may be road, vehicle and the user. The poor condition of the road, poor design features of the road, factors resulting from weather conditions, visibility problems, flow conditions, obstructions, delays etc. contribute increased chances of accidents. The poor condition of the vehicle, poor maintenance, speed parameters, control features, accelerates the chances of accidents. The behaviour of the driver, road user, fatigue, continuous driving, and effect of intoxication at various levels contribute much to the accidents. While transporting hazardous materials, other than the toxicity or flammability of the material, these factors also will be contributing to the accident. The pressure conditions, temperature conditions, exposure levels of the chemical etc. add still more. So it is highly relevant to conduct a study on quantitative risk analysis embedded with the causes of accidents.

The statistics published by the Government of Kerala revealed that urban road crashes increased by 37% from 2009 to 2012. Nearly 20% of these accidents occur at intersections. There was an annual increase of 10 to 15% in the overall number of accidents. The accident mortality rate was increasing on an average of 15% per annum, comparing to the previous year.

The number of vehicles in the road is increasing every year, but the road dimensions are not changing. The stakeholders affected by the incidents are seriously affected, even though the number is limited.

The guidelines and operational manuals are available to reduce the risks during transportation of hazardous materials. But detailed study correlating the accident causes and quantitative risk assessment was not taken place. This is a humble step to investigate the scope for the correlation and development of accident causation model with QRA in transportation of Hazardous Materials.

The entire research can be divided into three phases. The first phase comprises the analysis of accidents based on various parameters in selected stretches of the National Highway. This analysis will be the basis for the development of the accident causation model. The second phase comprises the analysis of accidents during hazardous material transportation in any stretch of the Highway. Third phase is the investigation to link the causative factors of the two. Thus identification of the basic nature of accidents happening in the selected highway stretches, identification of the root cause of the accident based on the collected data, identification of the features of the road contributing to the accident, identification of the influence of road geometry with accidents, identification of the road intersection type contributing to more frequent accidents, identification of the hazards and threats from credible road accident scenarios during Hazardous Material transportation, modelling of the credible road accident scenarios during Hazardous Material transportation, identification and quantification of the individual risks and societal risks due to this, and finally the appropriate modification of the identified road intersection will become the objectives of the research in a broader sense. In particular, the objectives are:

- To develop accident causation model for signalised intersection, non-signalised intersection, roundabouts and road curves of varying topographical conditions with specific reference to Hazardous Material transportation.
- To identify the hazards and threats from credible road accident scenarios during Hazardous Material Transportation.
- To develop the criteria for judging the tolerability of risks by constructing F-N diagrams.
- To generate projected consequences and compare the results of QRA

The accident data collected from three different sections of National Highway 544 (old NH 47) was used for road accident cause analysis. The accidents reported from Kerala state in general used for the accidents related with hazardous material. The CCPS-CPQRA model describes the methodology for quantitative risk analysis. IS 15656: 2006- code of practice, by Bureau of Indian

Standards provides the guideline for hazard identification and risk analysis. Data analysis (primary and secondary) is done with various statistical tools.

As part of the analysis, primarily data collected from various government agencies in Kerala, related or involved in the accident scenes, like Kerala Police and Fire & Rescue departments. Then various HazMat transportation agencies, factories or industries from which the HazMat was transported/ to which the HazMat was transported, Industrial Safety Department- Government of Kerala and Government of India, National and international agencies monitoring the HazMat incidents, National Highway Authority of India and Journals analysing the HazMat incidents.

From the collected data, the basic classification of accidents was done based on the nature of accidents for a particular period. Then basic causes behind the accidents were identified. Five specific causes and one general cause to indicate all other types were used for the analysis. Then the road features in controlling the flow was identified. After that the conditions of the road, geometric feature of the road and horizontal and vertical profile of the road was identified and used in the analysis.

The accident causation model for general transport system is available in various countries according to the climatic conditions and territorial characteristics. Accident causation studies with hazardous materials (handling, packing, filling, carrying etc.) also are available. But accident causation model with specific reference to the Hazardous Materials during transportation is not available. The intersection analysis incorporating the transportation risks of Hazardous Materials is seldom available. In this study, the causative factors of general road accidents were analysed, which will be the basis of any accident causation model. Then the additional factors contributed in the accidents during road transportation of Hazardous Materials in a mixed of variety of road conditions discussed. Scope for developing an accident causation model during hazardous material transportation was explored.

Being a broader area to study with limited time and resources, this research is focussed on road transportation (highway transportation) of HazMat than any other mode like rail or air. Scope is limited to incidents occurred during transportation; and not during packing, filling, loading or unloading of hazardous materials. Also incidents involving bulk transportation only considered. Since detailed analysis of all incidents involved in all HazMat transportation cannot be considered and analysed in this research, it is limited to two HazMat based on the available data, because of research constraints. While developing the accident causation model, intersections, roundabouts and road curves and certain linear stretch of the highway only included.

The sequence of operations can be summarised in the form of a general flow diagram of QRA. The procedure can be summarized as 1) QRA objectives 2) Process description, 3) Hazard identification 4) Scenario selection 5) Consequence analysis, frequency estimates and Risk estimation. The typical work done is:

1. The general accident data for Kerala State was collected for a few years. Then the causative factors behind the accidents were analysed.
2. Other accident parameters related to Driver, Vehicle and Environment was analysed. Environmental factors and the Hazardous Material analysis were done with two chemicals, one flammable and the other one non-flammable. The flammable material is Liquefied Petroleum Gas (Butane) and the non-flammable material is Chlorine gas. The transportation of these materials under high pressure in liquid form in bullet tankers were considered. The identical incidents happened in the highway stretches were replicated with similar values to make the model. The analysis was done in ALOHA and plotting done with MARPLOT. Results were checked with the actuals. And potential directions in case of wind direction change also was analysed.
3. The second main reason behind the accident is the design condition of the roads. Intersection analysis was done for a typical signalised road junction and

the possible conversion of it into a roundabout using Sidra Intersection software. The design details are furnished.

The relevant statistical tools were used as and when required for analysing the data and presenting it in the form of comparison charts, pie diagram, line diagram, etc. ALOHA software is used for modelling, consequence and effect analysis. MARPLOT software was used to interpret spatial data and SIDRA Intersection analysis used for detailed design and analysis of the road geometrical feature.

In this study, two chemicals LPG as well as Chlorine is used for analysis. LPG is used as a fuel in domestic areas and industrial areas. In case of leaking, the vessels containing LPG can release the liquid which quickly vaporizes, or the gaseous mixture.

The chemical Chlorine gas is highly toxic by inhalation. Generally the odour threshold is 3.5 ppm. Chlorine has the rate of onset immediate to hours while persistence is minutes to hours. Chlorine is used as a cleaner/disinfectant in many industries; water treatment; with irritating fumes are heavier than air. Chlorine is highly reactive.

In the present study, case studies of TT accident carrying LPG as well as Chlorine gas has been analysed in detail using ALOHA (Area Locations of Hazardous Atmospheres) simulation codes. Many models are available for analysis. The solid flame model by Roberts which is used in the ALOHA is considered for this study.

While doing the analysis, it is found that the rupture of the tank is initiated by a leak through a small hole in the tanker developed due to the accident. The gas release and subsequent pressure conditions was extensively used for the analysis. Further to that, the relationship with the last known speed of the vehicle which is causing the accident and the actual measured values of the hole sizes developed in the tank body is explored in this study. This is based on the data available from various TT incidents as well as traffic records.

Comparing to the general road accident cases, the accidents with HazMat is also similar in happening, when we consider the initial part. But the severity of the accident is increasing just after the accident due to the release of hazardous chemicals and its consequence.

Risk is defined as a function of hazard, hazard frequency and hazard consequences. QRA start with identifying accident scenarios, and Risk is presented generally as location specific individual risk or individual risk. Location specific individual risk provides a measure of hazard associated with different geographic locations within a facility. The assumption is that each target location is permanently inhabited by a single individual. The calculated risks are given as risk contours. Individual risk is determined on a case to case basis for each individual working in a facility. The contribution of individual risk is evaluated as a time weighted average of the LSIR values at each locations at which the work group will be exposed. F-N curve also called societal risk is a plot of the cumulative frequency of events resulting in N or more fatalities against N.

Both the chemicals, flammable and non-flammable, was analysed with the model by running it again for various sizes of openings, resulting in the release of LPG/ Chlorine in varying quantities. The drain pipe hole size assumed were 2 cm, 3cm and 4 cm and the affected distance and affected area are plotted for different thermal radiation levels. It gives indication of the zone in which rescue operations are to be started immediately.

Consequence modeling, its effect and risk calculations are evident from the threat zones marked in various figures. The cases discussed are belonging to the categories are jet fire due to leakage from holes in the bottom of tanks (cracks in the drain pipes) carrying LPG after overturning the tanks in accident, pool fire with vapour cloud due to the leakage from holes in the bottom of tanks cracks in the drain pipes carrying LPG after overturning the tanks in accident and threat zone without fire due to the leakage from holes in the bottom of tanks cracks in the drain pipes carrying LPG after overturning the tanks in accident.

As a simplified approach, weather conditions are assumed to be stable in the model while making the plots. Individual risks for thermal radiation and vapour cloud explosion were plotted and safe distance marked in the graph as well as in the maps.

The number of overturning cases in which the toxic release was happened through a tank opening (drain pipe crack and subsequent release of chemical) against the last known speed of the vehicle is made. Even though direct correlation is not there with the speed and hole size, it can be used as an indicator in the calculation of affected area or affected distance in case of a toxic release as BLEVE or Jet fire as in the real incidents.

Based on the data, if we plot the last known speed of the vehicle before overturning and the maximum size of the hole developed in the tank due to overturning, different correlations are possible.

As per the logarithmic plot, the trend line equation as $y=8.882\ln(x)+2.2549$ where y is the developed hole size in the tank corresponding to a speed in kmph. The R^2 value is 0.8756. But on analysis, the real values are different from the trend line values in lower speed ranges as well as in the higher speed ranges. So this cannot reflect the real incident scenario.

A power plot gives the trend line equation as $y=4.931x^{0.7002}$ where y is the developed hole size in the tank corresponding to a speed in kmph. The R^2 value is 0.9515. In this case, in the lower speed ranges as well as in the upper speed ranges, the trend line is slightly deviating from the observed data. So this also will not reflect the real scenario. An exponential plot gives the trend line equation as $y=5.2734e^{0.1858x}$ where y is the developed hole size in the tank corresponding to a speed in kmph. The R^2 value is 0.9709. On analysis the trend line best suits for the speed ranges up to 45 kmph, but in higher speed ranges the tentative values are either on the upper side or on the lower side than the real values. The number of cases when we considered, only 17 cases out of 78 is falling in this range. In the real sense, 45 kmph is only the permissible speed in the sector and not an over speed, the attribute "over speeding" will not be justified.

A linear plot gives the trend line equation as $y=2.4833x+2.4722$ where y is the developed hole size in the tank corresponding to a speed in kmph. The R^2 value is 0.9923 which indicates a high degree of correlation. The trend line very well explains the data within the speed range of 55 kmph and above, which is generally an over speed in majority of the road sectors.

A slight modification of the linear trend with a second degree polynomial plot gives the trend line equation as $y=0.0314x^2+2.1695x+3.0476$ where y is the developed hole size in the tank corresponding to a speed in kmph. The R^2 value is 0.9931, which is better than 0.9923. Also it gives better predictions from a speed range of 48 kmph.

In the broader context, correlation will not reflect all causative factors and all correlations may be causative in nature. But here, when comparing the real scenario, the over speeding and thereby overturning of the vehicle is the causative factor. It is becoming highly risky because of the toxic release through the holes developed in the tank, because of the effect of overturning.

In Summary, a three dimensional dynamic problem of movement of a HazMat in the bullet tanker can be analysed in the accident scenario, with known limited parameters. Once the HazMat transport vehicle is over speeding and because of that if it gets overturning, the entire moving tank is coming to standstill and all the variables of speed is getting eliminated. This redundancy in speed will make the accident condition as simple as a tank source is leaking with certain known parameters, which can be analysed with ALOHA either under BLEVE or jet fire as the case may be. The results obtained in this analysis are more or less same as that of the accident scenario where severe burns and multiple devastations have happened in the threshold zones. So the accident causation model suggested is valid and can be used for similar cases.

This research has the following main outcomes:

i. Comprehensive list of the causes and effects of various road accidents were made. This was correlated to the Driver, Vehicle and Environment parameters to develop the causation model.
ii. Credible road accident scenarios during HazMat transportation was modeled. Hazards, threats and influential areas identified.
iii. Societal Risks was examined based on the tolerability of risks by constructing F-N diagrams.
iv. Projected consequences at a distance of 1 km was calculated and compared with the QRA.
v. Detailed analysis of the intersections based on the causation model was done with latest transportation parameters (flow, volume, lane conditions etc. for signalised intersections and non signalsied intersections. Accident causation model for various risk criteria developed and discussed.

Based on the above results it is easy to understand that any modification made on the traditional road geometry may improve the driver characteristics and thereby it can be a causal factor in reducing the accidents. Many researchers already discussed this in detail. As in the case of ICT devices being a causal factor in reducing the number of road accidents, smoothening of the traditional bottlenecks in traffic may enhance the safety related to traffic. The number of conflict points are reduced considerably in the roundabout design, possible collisions are also will be reduced. One serious problem that may arise, and has to be analysed in detail in further studies is the probability of accidents because of the increased speeds in movements in the roundabouts in comparison with the intersections.

The major gap in this research is that, it starts with a real failure scenario, based on the past history. But historical frequencies vary depending on the location, climatic conditions and time of occurrence. In most of the cases, mitigative measures taken and the rescue operations made are explored while the causal mechanism is not explained. Assumptions are sometimes not transparent.

Generally certain limitations are there in QRA. The major limitation is that the assumptions are not visible to all concerned, only the developer of model can explain. Also, the models are static, difficulties to incorporate changes or variations; it is difficult to change and requires considerable specialist efforts and time; software used are costly, and proprietary, calculations are not transparent.

If extensively developed, the proposed accident causation model can be extensively used for re-planning the intersections, modifying the road contours with varying topographies, channelising or segmenting the traffic at potential hot spots with proper consideration to the hazardous material transportation. Moreover, the traffic analysis with single lane conditions, multilane conditions, two directional flow conditions, etc. also can be made specific with the associated risks. Various control measures also can be planned based on the analysis. The causation model prioritizes the root causes of an accident, which will be useful to control/manage the present transport risks and to refine future studies. Also it will be useful to identify and to establish points of strategic importance in the emergency responses based on IVMS input during Hazardous Material transportation.

LIST OF SYMBOLS

Symbol	Expansion
atm	atmospheric pressure
cc	Cubic centimetre
C	Celsius
F	Fahrenheit
F-N	Frequency against Number of fatality
J	Joule
kg/m^3	kilogram per cubic metre
kmph	kilometre per hour
kW/m^2	kilo Watt per square metre
m	metre
MJ/kg	Mega joules per kilogram
ppm	parts per million
veh/h	Vehicles per hour
v/v	volume per volume percent

LIST OF ABBREVIATIONS

Abbreviation	Expansion
AEGL	Acute Exposure Guideline Level
ALOHA	Areal Locations of Hazardous Atmospheres
BIS	Bureau of Indian Standards
BLEVE	Boiling Liquid Expanding Vapour Explosion
CCPS	Centre for Chemical Process Safety
CPQRA	Chemical Process Quantitative Risk Assessment
CPR	Cardio Pulmonary Resuscitation
DVE	Driver Vehicle Environment
EPA	Environmental Protection Agency
ERG	Energy Resources Group
HazMat	Hazardous Materials
HCM	Highway Capacity Method
HFF	Human Functional Failure
ICT	Information Communication Technology
IR	Individual Risk
IVMS	In Vehicle Monitoring System
KP	Kerala Police
LEL	Lower Explosive Limit
LFL	Lower Flammability Limit
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSIR	Location Specific Individual Risk
MIS	Management Information System
NH	National highway
NHAI	National Highway Authority of India

NIOSH	National Institute for Occupational Safety and Health
OISD	Oil Industry Safety Directorate
OTS	On The Spot
PCU	Passenger Car Unit
QRA	Quantitative Risk Assessment
RH	Relative Humidity
SDMA	State Disaster Management Authority
SH	State Highway
SS	Stainless Steel
TNT	Tri Nitro Toluene
TRA	Transportation Risk Analysis
TT	Truck Tanker
UEL	Upper Explosive Limit
UFL	Upper Flammability Limit
UN	United Nations
USCG	United States Coast Guard

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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

The current research work is intended to make the quantitative risk assessment of the hazardous materials during the road transportation and to develop an accident causation model. In this chapter the statement of the proposal, the background of the research and motivation for doing the research is examined. Why a research is needed in this field, the objectives of the research and scope of the research is examined. The theoretical framework of the research, the sources of data and the tools that can be used for analysis also explained.

1.2 STATEMENT OF THE PROPOSAL

A number of incidents involving the release of toxic chemicals are reported leading to serious consequences during the transportation of Hazardous Materials (HazMat). Most of the hazards can be eliminated or limited to a minimum through the use of risk analysis. A powerful tool like Transportation Risk Analysis (TRA) can be used to select the most suitable alternative with a reduced risk.

The various risk components like frequency, risk scenario, risk consequence, and likelihood are to be properly mapped with the selected route to obtain the best output [1]. But due to the changes in urbanization, the characteristics of the neighbourhood of selected route are changing, resulting in a serious consequence.

The attributes resulting in accidents can be related to the road, vehicle, user or environment. The initiating events of accidents, the outcomes of the incident, meteorological conditions, population, and time of occurrence, all have influence in determining the severity of accidents. A model incorporating the various causes of accidents and its effects on neighbourhood population during HazMat transportation based on decision support system is not available. This research is an attempt to link Quantitative Risk Assessment (QRA) of HazMat during road transportation with accident causation models, using the real incident data from Kerala.

1.3 BACKGROUND AND MOTIVATION

Transport operations of hazardous materials have greater risks during the entire stretch of transportation. Even if low frequency and high impact incidents are reported, it has caused in significant human loss in the industry. Environmental damage also is very high. But, every accident is associated with different type of failures with different root causes. An analysis of the pattern of accidents and occurrence of incident with root causes can act proactively to prevent or to reduce loss or damages [2].

Kerala, one of the densely populated state is having limited transportation facilities. The scope for development of the transportation sector is also limited because of the increased population density [3]. But the hazardous material movement is taking place through the crowded routes during all times. Many incidents were reported, resulting in the human loss, time loss, damages due to pollution, traffic delay, evacuation of the neighborhood and fire. The preparedness of the society as well as the carriers is to be analysed. The probability of the risks are to be reduced and the damages to be minimised.

The factors involved in the accidents may be road, vehicle and the user [4] . The poor condition of the road, poor design features of the road, factors resulting from weather conditions, visibility problems, flow conditions, obstructions, delays etc. contribute increased chances of accidents. The poor condition of the vehicle, poor maintenance, speed parameters, control features, accelerate the chances of accidents. The behaviour of the driver, road user, fatigue, continuous driving, and effect of intoxication at various levels contribute much to the accidents. While transporting hazardous materials, other than the toxicity or flammability of the material, these factors also will be contributing to the accident. The pressure conditions, temperature conditions, exposure levels of the chemical etc. add still more. So it is highly relevant to conduct a study on quantitative risk analysis embedded with the causes of accidents during the transportation of hazardous materials.

1.4 NEED FOR THE RESEARCH

The statistics published by the Government of Kerala revealed that the road accidents are increasing year by year. The urban road crashes increased by 37% from 2009 to 2012. Nearly 20% of these accidents occur at intersections [5]. There was an annual increase of 10 to 15% in the overall number of accidents. The accident mortality rate was increasing on an average of 15% per annum, comparing to the previous year. When we benchmark the accident statistics to a particular year, the increase is alarming.

The number of vehicles in the road is increasing every year, but the road dimensions are not changing. Flow conditions of the road is becoming unfavourable to the smooth traffic[3]. The Hazardous material transportation also is taking place through these busy streets. The reported incidents are increasing 10 to 15% per year, but the severity is manifold comparing to the benchmark years. The stakeholders affected by the incidents are seriously affected, even though the number is limited.

The guidelines and operational manuals are available to reduce the risks during transportation of hazardous materials. But detailed study correlating the accident causes and quantitative risk assessment was not taken place [5]. This is a humble step to make the correlation and develop an accident causal model with QRA in transportation of HazMat. The experience of the researcher in numerical modelling and spatial analysis motivate to fine tune the model.

1.5 OBJECTIVES AND SCOPE

The entire research can be divided into two phases. The first phase comprises the QRA during TRA and the second phase the development of an accident causation model.

1.5.1 The objectives:

i. To develop accident causation model for signalised intersection, non-signalised intersection, roundabouts and road curves of varying topographical conditions with specific reference to HazMat transportation.
ii. To identify the hazards and threats from credible road accident scenarios during HazMat Transportation.
iii. To develop the criteria for judging the tolerability of risks by constructing F-N diagrams.
iv. To generate projected consequences and compare the results of QRA.

1.5.2 Scope of the research:

- This research focussed on road transportation (highway transportation) of HazMat than any other mode like rail or air.
- Incidents occurred during transportation only considered; and during packing, filling, loading or unloading was not to be considered.
- Incidents involving bulk transportation only considered.
- Incidents involved in all HazMat transportation can not be considered and analysed in this research. It is to be limited to two HazMat based on the available data, because of research constraints.

- While developing the accident causation model, intersections, roundabouts and road curves only considered. Entire linear stretch of the highway cannot be included.

1.6 RESEARCH FRAMEWORK

1.6.1 Flow Diagram of QRA

The sequence of operations can be summarised in the form of a general flow diagram of the procedure used for QRA [6] is given in Fig 1.1.

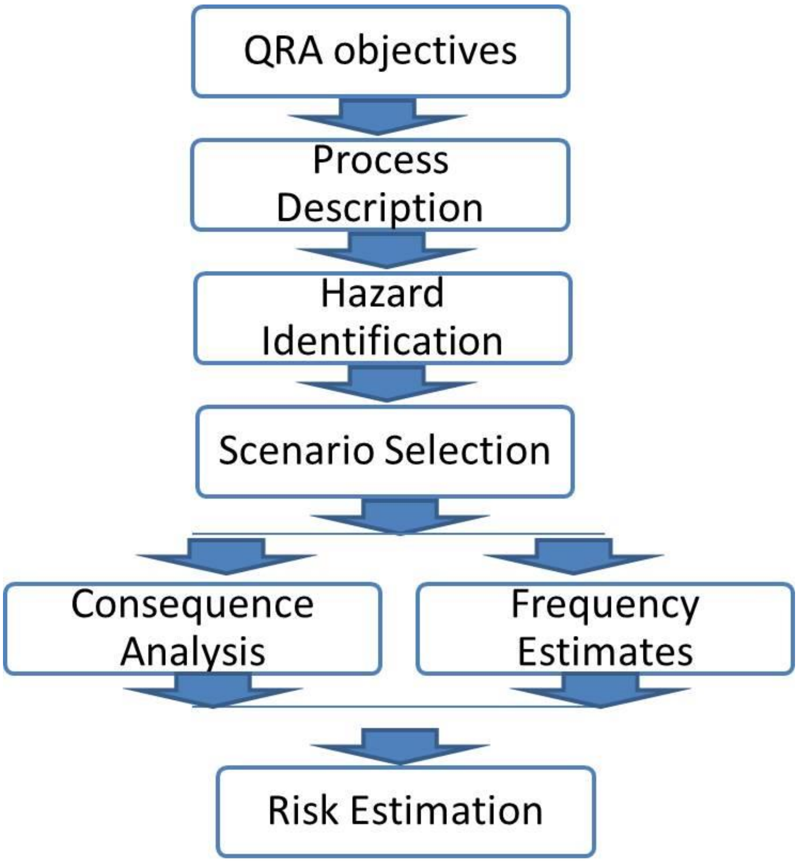

Figure 1.1 Flow Diagram of QRA

1.7 STRUCTURE OF RESEARCH WORK

1. The general accident data for Kerala State was collected for a few years. Then the causative factors behind the accidents were analysed.
2. Other accident parameters related to Driver, Vehicle and Environment was analysed. Environmental factors and the Hazardous Material

analysis were done with two chemicals, one flammable and the other one non-flammable. The flammable material is Liquefied Petroleum Gas (Butane) and the non-flammable material is Chlorine gas. The transportation of these materials under high pressure in liquid form in bullet tankers were considered. The identical incidents happened in the highway stretches were replicated with similar values to make the model. The analysis was done in ALOHA and plotting done with MARPLOT. Results were checked with the actuals. And potential directions in case of wind direction change also was analysed.

3. The second main reason behind the accident is the design condition of the roads. Intersection analysis was done for roundabout and signalised intersection using Sidra Intersection. The design details are furnished.

The research is broadly organized as in Fig 1.2 as follows:

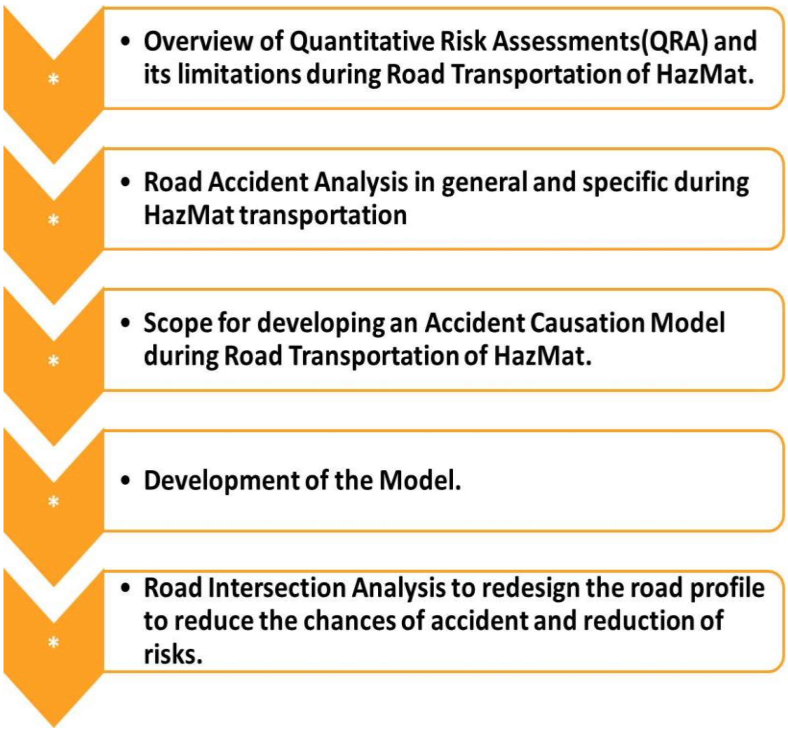

Figure 1.2 Research Organisation

1.7.1 Theoretical framework

The CCPS-CPQRA model describes the methodology for quantitative risk analysis. IS 15656: 2006- code of practice, by Bureau of Indian Standards provides the guideline for hazard identification and risk analysis.

1.7.2 Source of Data

The source of the data:

- Primarily data collected from various government agencies in Kerala, related or involved in the accident scenes, like Kerala Police and Fire & Rescue departments.
- Data collected from various HazMat transportation agencies.
- Data collected from factories or industries from which the HazMat was transported/ to which the HazMat was transported.
- Industrial Safety Department, Government of Kerala and Government of India.
- National and international agencies monitoring the HazMat incidents.
- Journals analysing the HazMat incidents
- National Highway Authority of India.

1.7.3 Tools

- The relevant statistical tools as and when required (comparison charts, pie diagram, line diagram, etc.)
- MARPLOT to interpret spatial data
- ALOHA for consequence and effect analysis /modelling
- Other relevant TRA and QRA tools.
- SIDRA Intersection analysis

1.8 CHAPTER SUMMARY

In this chapter the statement of the research proposal, the background of the research, motivation for doing the research, why a research is needed in this field, the objectives of the research and scope of the research is examined. The theoretical framework of the research, the sources of data and the tools that can be used for analysis also explained.

CHAPTER 2
LITERATURE REVIEW

2.1 OVERVIEW

In this chapter, related previous research findings in the topic areas are explained. The broad area of QRA and how many researches used the tools in QRA, various conditions of the road and road features, various accident studies conducted, the details of the hazardous materials like LPG and chlorine during their transport, various risks involved in the transportation processes, different accident analysis models available and how the researchers utilised them is explored.

2.2 QUANTITATIVE RISK ASSESSMENT

Road transportation of dangerous goods, especially the aspects of Quantitative Risk assessment and route comparison is discussed by Philip Cassini [1]. The framework of the model can be developed based on this. Then the scope for incorporating decision making strategies in QRA framework to be identified. B Fabiano et al, in framework of risk assessment [7], suggested the decision making strategies to be adopted in dangerous goods transportation. Focussed on the offsite transportation of inflammable hazardous waste materials, Arup Das et al, suggested Comprehensive risk assessment framework[8], with a potential to establish a link while assessing the risk related with the hazardous materials.

After the risk assessment, then techniques to reduce the risk in various transportation system has to be analysed. Xiang Liu et al [9] suggested the framework to improve risk reduction in rail transport system. The elements and outcomes from this study can be effectively used in the linear/segmented road transportation. The detailed guidelines for hazardous material transportation suggested by Guidelines for QRA during transport of HazMat [10] published by Singapore Government provides detailed insight into this area.

During transportation, in the event of a disaster or exposure, the mitigation of the disaster is important. The nature and management of disaster in the event of a HazMat incident in a transportation network was explained by James H L et al in Disaster evacuation in transport [11]. Consequence analysis can be framed from this study. Moreover, the Exposure condition analysis to reduce risk during transport of dangerous goods in rail / road transport network, suggested by Manish Verma, in "Minimisation of transport risk" [12], helps in assessing the severity of consequences.

Passive fire reduction methods during LPG transport suggested by Nicola P et al [13] emphasizes how to reduce the risk during the transport of LPG through road and rail; which can be extensively used in reducing the flammability and thereby to reduce the severity of the disaster. The risk to the environment during HazMat transportation through railway in case of a release, analysed by Mohd Rapik Saat [14] resembles the situation in a linear transportation segment of a highway. This risk studies along with probability analysis of risk during transport of HazMat [15] can be extended to have the multivariate intersection analysis of road.

2.3 ROAD AND ROAD FEATURES

On featuring the characteristics of the accidents on roads, Asha [16] proposes the use of Information Communication Technology in reducing road accidents in Kerala. In this study, speed is considered as the root cause of general traffic accident and its controls suggested.

In the undivided highways, the randomness in the potential movement of a vehicle causing to an accident is increased, compared to the disciplined flow of lane traffic. Random parameter models are significant in such situations. R R Dinu and A Veeraragavan discusses the random parameter models for accident reduction [2] for considering in the prediction of two lane undivided highways.

The fatality of accidents is not depended on the time at which it has happened. But the chances of survival of a victim highly depends on the minimum response time and the proper attention available to him/her in the minimum time. The traffic congestions, in one way increases the attention time and delays the rescue operations while odd time incidents delay the attention as well as rescue. The indicators available to the rescue team also are important. An in depth analysis for the scope for researching fatality rate reduction with evidence for time invariance and state specificity was done by Raj in Road traffic fatalities studies [17].

In signalised intersections, the randomness of the vehicular movement is avoided and a controlled movement only is permitted. The stream and flow is predetermined and the time of flow also is decided. In such cases the chances of accidents are merely due to violation of the flow behaviour or unlawful entry to the stream other than the sudden vehicular failures. Severity of the accidents in such intersections can be analysed at specific crash severity levels. Abdel et al [18], identified the scope and potential of the analysis of specific crash severity levels at signalised intersections.

2.4 ACCIDENT STUDIES

Accident spot studies reveal that there is a clear time gap between the occurrence of accidents (crash) and the spontaneous response towards a potential accident. Many factors including the conditions of the vehicle, environment and driver behaviour acts before the crash. If parametric estimation of these factors can be made, then prediction of the crash is possible; but not complete avoidance of the crash. A probabilistic approach of crash prediction, Bayesian hierarchical approach of prediction models, was suggested by Huang H, in his Crash prediction model [19]. But it is highly mathematical in nature and the practical relevance as well as usefulness has to be proved yet at various accident spots at various environments.

Accident severity depends upon many factors. The data collected from the accident spot as well as from the interrogating agencies will give an insight. In many cases the data entered in the insurance files also reveal many contributing factors. Severity analysis is complex because of the variables and their interrelations. Rifaat S et al, generated accident severity analysis [20], using probit model. The way in which the complexities are related to the particular accident scenario may not be a replica of a repeated accident in another topography and climatic conditions, where the model has its major limitations; and the severity classification in various countries are not the same.

Identification of the accident hotspots was another concern. If the number of accidents happening in the same spot or in the same stretch are more, it was considered as the accident hotspots. The characteristics of the accidents and remedial measures can be thought of, if clustering of accidents are made. Prasannakumar V et al, in their approach of spatiotemporal clustering of accidents [3], made a significant attempt to identify accident hot spots by GIS analysis and clustering. Only a small area was brought under the study and there is a scope to include it in the longitudinal stretches of the highways.

Roundabouts are always vulnerable spots for accidents. The "speed non-reduction tendency" of the approaching vehicles seems to be a significant cause in majority of the accidents in roundabouts. The design parameters like roundabout radius, the lane width, extra width required for the alignment changes, etc. are to be dealt with proportional significance. Anjana S et al [5], tries to have a safety evaluation tool for roundabouts, using statistical techniques incorporating more geometric variables with a potential scope for accident prediction models.

Road safety measures can be categorized as user related measures, training and education, traffic law, incentive, enforcement and vehicle related measures as suggested by Jacob Thomas [21]. The application of ICT measures will be belonging to the areas like training and education, traffic law enforcement, vehicle related measures and infrastructure related measures.

Road safety is known to be influenced by factors such as weather changes, increased police and camera based enforcement, hot spot remediation programs as suggested by David Wallington et al [22]. Enforcement of the speed control regulations and effective monitoring of speed limits of vehicles at various stretches by ICT aids of the road is important in this aspect.

So Young Sohn [23] suggested that area specific control policy if adopted would minimize various severity levels of road accidents such as deaths, major injury, minor injury and property damage. It requires the usage of a systematic approach to derive local specific policy to deal with several severity types of accidents along with bench marked information. Effective police alert can ensure the physical presence of enforcement team which can extend the scope in the collection of data and integration of MIS.

Ross Oven Philip et al [24] suggests that various enforcement strategies including safety campaigns can reduce the number of road accidents. Intoxicated or drunken driving is a menace, which accelerates the road accidents, and can be controlled properly if the intoxicated persons are caught easily and penalized appropriately.

William Young et al [25] assess the state of the art in the use of computer models to simulate and assess the level of safety in existing systems. While ascertaining that there is no single measure, which will link deriving environment, events or behavior or crashes to provide a single measure of the safety for all the parts of the road system, he suggests checking which one or which combination will work exactly.

W. Murray et al [26] recommend using Extensive Management Information System to allow the visibility of data and use of it to provide quantification of even individual interventions.

Significant findings of Kerala Police [27] is that increasing deaths in road accidents are due to the reasons related to the driver of the vehicle with wrong driving habits and aggressive driving, over-speeding and drunken driving. Ignorance of the rules and violation of the rules and poor road conditions play other vital role. Based on the analysis it is understood that there is a tremendous scope for incorporating ICT aids at various levels in reducing the road accidents in Kerala. Available literature does not explain the status or extent of the influence of ICT aids in the monitoring or control of road accidents in Kerala.

2.5 HAZARDOUS MATERIALS: LPG

Based on the general road accident data, many accident causation models were suggested. In these accident causation models, the framework of accident description starts with the Driver-Vehicle-Environment model (DVE model) which is the most accepted one. In the functional point of view, the DVE system processes were explained through Human Functional Failure (HFF) model. Later, 'On The Spot' (OTS) model was suggested. In all these models, various parameters as we discussed in the accident scenario only was considered. The causative factors during hazardous material transportation was not specifically mentioned in these models.

In the present study, two chemicals LPG as well as Chlorine is used for analysis in case of a leak and disaster. As per Cameo [28], the chemical Library combined along with the ALOHA software[29], the general details of both the chemical can be summarised as follows:

The name of the flammable chemical is generally known as LPG, Liquefied Petroleum Gas coming under the hazard label, “flammable gas” which is informed as “highly flammable” as per the reactivity alert. It is a petroleum product containing a mixture of propane, propylene, butane, butylene, isobutane, and other low molecular weight hydrocarbons that is refined from petroleum which is heavier than air. The same chemical may alternately know in chemical names such as Bottled gas, Burshane, Compressed petroleum gas, Liquefied hydrocarbon gas, Liquefied petroleum gas , LPG, L.P.G, Propane-butane-(propylene) and Pyrofax.

LPG is used as a fuel in domestic areas and industrial areas, an aerosol propellant, in cigarette lighters, and to make other industrial chemicals. Generally it is kept as a liquid under high pressure. In case of leaking, the vessels containing LPG can release the liquid which quickly vaporizes, or the gaseous mixture. Being the LPG heavier than air, a flame can flash back to the source of the leak very easily. Under prolonged exposure to heat the containers may rupture violently and rocket. LPG has no reaction with water.
The fire hazard due to LPG detailed and provided in Excerpt from GUIDE 115 [Gases - Flammable (Including Refrigerated Liquids)] is as follows: “Extremely flammable. Will be easily ignited by heat, sparks or flames. Will form explosive mixtures with air. Vapours from liquefied gas are initially heavier than air and spread along ground”. [30]

The same guide cautions that since the LPG contains Hydrogen, Deuterium, Hydrogen-refrigerated liquid and Methane which are lighter than air and will rise. In case of a fire, Hydrogen and Deuterium burn with an invisible flame and so very difficult to detect with normal eyes. An alternate method of detection with devices like thermal camera, broom handle, etc. may be required. “Vapours may travel to source of ignition and flash back. Cylinders exposed to fire may vent and release flammable gas through pressure relief devices. Containers may explode when heated. Ruptured cylinders may rocket”. [30] In the instruction to fire fighters, it is clearly mentioned that do not try to extinguish a leaking gas fire unless leak can be stopped because of the chance that Hydrogen and Methane mixture, compressed may burn with an invisible flame. In case of small LPG fires, the use of dry chemical or CO_2 is advised. At the same time, large fires can be controlled by water spray or fog, but, ensure to move containers from fire area if it can be done without risk. It is suggested to fight fire from maximum distance or use unmanned hose holders or monitor nozzles in the case of fire involving tanks. Cooling of containers by flooding exorbitant quantities of water is recommended until fire is put out. At the same time it is cautioned that do not direct water at source of leak or safety devices because of the fear of icing. In case of rising sound from venting safety devices or discoloration of tank, do not harm them by staying there and withdraw immediately. It is better always to stay away from tanks engulfed in fire. For any type of massive fire, use unmanned hose holders or monitor nozzles; if this is impossible, withdraw from area and let fire burn. [30].

Considering the health hazards, high concentrations of LPG can cause asphyxiation. If LPG concentrations in air are 1%, it may cause dizziness in 10 minutes and concentrations greater than 10% may cause dizziness in a few minutes. [31]

Reactivity group of LPG is provided as “Hydrocarbons, Aliphatic Saturated”. The reactivity profile of saturated aliphatic hydrocarbons, contained in LPG, may be incompatible with strong oxidizing agents like nitric acid. There is a high possibility of occurrence of charring followed by ignition of unreacted hydrocarbon and other nearby combustibles. In the other settings, it is mostly unreactive. At the same time, it is not affected by aqueous solutions of acids, alkalis, most oxidizing agents, and most reducing agents.

The general recommendation for isolation in case of an LPG leak as an immediate precautionary measure is to isolate spill or leak area for at least 100 meters (330 feet) in all directions. In case of large spill, initial downwind evacuation should be done for at least 800 meters (1/2 mile). If tank, rail car or tank truck carrying LPG is involved in a fire, isolation should be done for 1600 meters (1 mile) in all directions; also, consider initial evacuation for 1600 meters (1 mile) in all directions. [30].

The guidelines as part of Non-Fire Response suggests the elimination of all ignition sources such as flares, sparks or flames in immediate area and advising no smoking. The equipment used for handling the chemical must be grounded. At the same time it is advised not to touch or walk through the spilled material. If possible, attempts can be made to stop the leak if it can be done without risk. Attempts can be made to turn leaking containers so that gas escapes rather than liquid.

Use water spray to reduce vapours or divert vapour cloud drift is encouraged. It is recommended to avoid allowing water runoff to contact spilled material and not to direct water at spill or source of leak. Measures are to be taken to prevent the spreading of vapours through sewers, ventilation systems and confined areas. Always it is better to isolate the area of leak until gas has dispersed. It is seen that when in contact with refrigerated/cryogenic liquids, many materials become brittle and are likely to break without warning; so additional care should be taken in this regard. [30].

The personnel engaging in the evacuation process or rescue operations or fire control operations should use Personal Protective Clothing and to use appropriate Personal Protective Equipment. Wearing appropriate personal protective clothing will help to prevent skin from becoming frozen from contact with the liquid or from contact with vessels containing the liquid. Burns or tissue damage from frostbite in eye or eye contact with the liquid can be eliminated by wearing appropriate eye protection devices. No recommendation is made specifying the need for washing the substance from the skin (either immediately or at the end of the work shift or to change clothing after the work shift. But work clothing that becomes wet with the flammable liquid should be immediately removed due to its flammability hazard (i.e. for liquids with flash point < 100°F). As a measure to improve the health and safety, quick drench facilities and/or eyewash fountains should be provided within the immediate work area for emergency use where there is any possibility of exposure to liquids that are extremely cold or rapidly evaporating. [32].

First Aid measures suggested if exposed to LPG includes the measures for eye, skin and breathing. Contact lenses should not be used while working with this chemical. If the chemical in liquid form contacts the eyes, washing the eyes with plenty of water and occasionally lifting the lower and upper lids are suggested. This has to be done immediately and then get proper medical attention immediately. If the chemical penetrates the clothing, removals of the clothing is suggested and if the chemical in liquid form contacts the skin immediately flush the contaminated skin with water. Because of breathing large amounts of this chemical, if a person suffers and have difficulty in breathing move the exposed person to fresh air at once. If breathing has stopped, perform mouth-to-mouth resuscitation. Keep the affected person warm and at rest and get medical attention at the earliest. [33]. Table 2.1 give physical properties of LPG.

TABLE 2.1 PHYSICAL PROPERTIES OF LPG

Parameter	**Value**	**Reference**
Flash Point	Propane: -156° F (cc); Butane: -76° F (cc).	(USCG, 1999)
Lower Explosive Limit (LEL):	Propane: 2.2 %; Butane: 1.8 %	(USCG, 1999)
Upper Explosive Limit (UEL):	Propane: 9.5 %; Butane: 8.4 %	(USCG, 1999)
Auto ignition Temperature:	Propane: 871° F; Butane: 761° F	(USCG, 1999)
Melting Point:	Data unavailable	
Vapour Pressure:	greater than 1 atm	(NIOSH, 2003)
Vapour Density (Relative to Air):	Data unavailable	
Specific Gravity:	0.51 to 0.58 at -58.0 ° F	(USCG, 1999)
Boiling Point:	greater than -40 ° F at 760.0 mm Hg	(USCG, 1999)
Molecular Weight:	greater than 44	(USCG, 1999)
Water Solubility:	Insoluble	(NIOSH, 2003)

2.6 HAZARDOUS MATERIALS: CHLORINE

As per Cameo, the chemical Library combined along with the ALOHA software, the general details of the chemical Chlorine can be summarised as follows:

The name of the chemical is generally known as Chlorine coming under the hazard label, “Poison Gas, Oxidizer, Corrosive” which is informed as “Strong Oxidizing Agent, Water-Reactive” as per the reactivity alert. Reactivity group of Chlorine is provided as “Oxidizing Agents, Halogenating Agents”.

Chlorine gas is highly toxic by inhalation. It is greenish yellow in colour with a pungent and suffocating smell, used to purify water, bleach wood pulp, and to make other chemicals. Generally the odour threshold is 3.5 ppm. It can be readily liquefied by pressure applied at room temperature and liquefies at -35°C under normal room pressure. Chlorine is slightly soluble in water. Density (as a liquid) is 1558 kg/m^3. Chlorine has the rate of onset immediate to hours while persistence is minutes to hours. Chlorine is used as a cleaner/disinfectant in many industries; water treatment; and as a war gas in world War I. Its irritating fumes are heavier than air.

Chlorine is highly reactive and it reacts explosively with numerous common materials or supports the burning of common materials. In the presence of soot, rust, carbon, or other catalysts chlorine ignites steel at 100° C and dry steel wool at 50° C. It explosively reacts as either a liquid or gas with alcohols, molten aluminium, silane and bromine pentafluoride. Other reactions with chlorine are:

a) naphtha-sodium hydroxide mixture (violent explosion)
b) wax (explosion)
c) methane over yellow mercury oxide (explosion)
d) carbon disulphide (explosion catalysed by iron)
e) 1-chloro-2-propyne (excess chlorine causes an explosion)
f) dibutyl phthalate (explosion at 118° C)
g) glycerol (explosion at 70-80° C)

h) Hydrogen (explosion initiated by light).
i) acetylene (explosion initiated by sunlight or heating)
j) ethylene over mercury, mercury(I) oxide, or silver(I) oxide (explosion initiated by heat or light)
k) gasoline (exothermic reaction then detonation)
l) zinc chloride (exothermic reaction)
m) diethyl ether (ignition)
n) diethyl zinc (ignition)

Either a liquid or a gas, chlorine reacts with:

a) Bismuth, Germanium, Magnesium, Potassium, Sodium, and Zinc.
b) Carbides of Iron
c) Uranium and Zirconium
d) Hydrides of Copper, Potassium and Sodium
e) Tin
f) Aluminium powder, Antimony powder, Calcium powder, Manganese powder and Vanadium powder
g) Aluminium foil, Brass foil, Copper foil,
h) Iron wire

When bubbled through cold methanol, chlorine causes ignition and a mild explosion. If we mix chlorine in excess with ammonia and make it warmed, it will explode or ignite. When coming in contact with hydrazine, hydroxylamine, and calcium nitride, it causes ignition. At the same time, with arsine, phosphine, silane, diborane, stibine, red phosphorus, white phosphorus, boron, active carbon, silicon, or arsenic it gets ignited or exploded. At ambient temperature chlorine ignites sulphides; and as a liquid ignites synthetic and natural rubber. Also it can ignite trialkyl boranes and tungsten dioxide. It forms explosive nitrogen trichloride from biuret contaminated with cyanuric acid. And readily forms an explosive N-chloro derivative with aziridine.

As part of isolation and evacuation, as per excerpt from GUIDE 124 [Gases - Toxic and/or Corrosive - Oxidizing], as an immediate precautionary measure, isolate spill or leak area for at least 100 meters (330 feet) in all directions. If tank, rail car or tank truck is involved in a fire, isolation is required for 800 meters (1/2 mile) in all directions; also, consider initial evacuation for 800 meters (1/2 mile) in all directions. [30].

The attempts to fire fighting starts with the evacuation of area endangered by gas. It is recommended to stay upwind; keep out of low areas by wearing positive pressure breathing apparatus and full protective clothing. Chlorine will not burn, but most combustible materials will burn in chlorine as they do in oxygen; flammable gases will form explosive mixtures with chlorine. Dry chemical, carbon dioxide, water spray, fog or foam can be used to control the fire. [34].

Chlorine may ignite other combustible materials like wood, paper, oil, etc. A mixture of chlorine with fuels may cause explosion. The container which carries chlorine may explode in heat of fire. If chlorine gas is present indoors, outdoors or in sewers, chances of vapour explosion and poison hazard are more. Hydrogen and chlorine mixtures (5-95%) are exploded by almost any form of energy (heat, sunlight, sparks, etc.). Chlorine emits highly toxic fumes when heated. As indicated in the reaction details above, it is better to avoid plastics and rubber coming in contact with it and also to avoid heat and contact with hydrogen gas or powdered metals. [34].

A mixture of hydrochloric acid and hypochlorous acids or its fumes are formed as water dissolves about twice its volume of chlorine gas. These acids are highly corrosive due to acidity and oxidizing potential.

Chlorine is considered as highly poisonous gas and causing very high degree of health hazard; it may be fatal if inhaled. Contact with chlorine may cause burns to skin and eyes and breathing may lead to Bronchitis or chronic lung conditions. [34].

The guidelines as part of Non-Fire Response (Non-Fire Response Excerpt from GUIDE 124 [Gases - Toxic and/or Corrosive - Oxidizing]) suggests not to touch or walk through spilled material and to keep combustible materials like wood, paper, oil, etc. away from spilled material.

The personnel engaging in the evacuation process or rescue operations should wear fully encapsulating vapour protective clothing for spills and leaks with no fire. Attempts to stop leak should be made if it can be done without risk. Water spray to reduce vapours or divert vapour cloud drift can be used but allowing water runoff to contact spilled material should be avoided. Never direct water at spill or source of leak and prevent entry of the liquids into waterways, sewers, basements or confined areas. Isolate area until gas has dispersed. Measures to ventilate the area may be very helpful. [30].

As a measure to improve the health and safety, quick drench facilities and/or eyewash fountains should be provided within the immediate work area for emergency use where there is any possibility of exposure to liquids that are extremely cold or rapidly evaporating [32].

First Aid measures suggested if exposed to Chlorine includes the measures for eye, skin and breathing. Contact lenses should not be used while working with this chemical. If the chemical in liquid form contacts the eyes, washing the eyes with plenty of water and occasionally lifting the lower and upper lids are suggested.

Effects due to the exposure to Chlorine may be delayed and thereby caution is advised. Since Chlorine is corrosive and may be converted to hydrochloric acid in the lungs, the symptoms may not appear immediately.
Rapid heart rate (tachycardia), high blood pressure (hypertension), followed by low blood pressure (hypotension), and cardiovascular collapse are the signs and symptoms of acute exposure to chlorine. Because of the effects in lungs, pulmonary edema and pneumonia are often seen. The eyes, nose, chest and throat may sting or burn following exposure to chlorine. Agitation, anxiety,

coughs with bloody sputum, dizziness, a feeling of suffocation, nausea and vomiting are common. Dermal exposure may result in blisters, irritation, pain and sweating.

When attempting for Emergency Life-Support Procedures, emergency personnel should wear protective clothing appropriate to the type and degree of contamination. Supplied-air respiratory equipment or Air-purifying respirator equipment should also be worn by the rescue persons, as necessary. Acute exposure to chlorine may require decontamination and life support for the victims. So rescue vehicles should carry supplies such as disposable bags to assist in preventing spread of contamination and chlorine-resistant plastic sheeting.

Steps to be followed as part of the First Aid for the victims of Chlorine inhalation exposure are:

a) Emergency personnel should avoid self-exposure to chlorine at the site. Then move the victims to areas with ample fresh air.
b) Evaluate the conditions of the victim. Check vital signs including pulse, respiratory rate and note any trauma. If no pulse is detected, immediately provide CPR. If the victim is not breathing, provide artificial respiration. If breathing is with difficulty, administer respiratory support or oxygen or other.
c) If it has to perform any other invasive procedures or for administration of an antidote, get authorization and/or further instructions from the local hospital.
d) Move the victim to a nearby health care facility.

In addition to the above, if it has been suspected that Dermal/Eye Exposure, follow these additional procedures:

a) Remove the contaminated clothing of the victim as soon as possible.
b) If eye exposure has occurred, at least for 15 minutes, eyes must be flushed with lukewarm water.

c) Exposed skin areas also should be washed for at least 15 minutes with soap and water

This has to be done immediately and then get proper medical attention immediately. If the chemical penetrates the clothing, removals of the clothing is suggested and if the chemical in liquid form contacts the skin immediately flush the contaminated skin with water. Because of breathing large amounts of this chemical, if a person suffers and have difficulty in breathing move the exposed person to fresh air at once. If breathing has stopped, perform mouth-to-mouth resuscitation. Keep the affected person warm and at rest and get medical attention at the earliest. [33].

Table 2.2 gives the physical properties of Chlorine. The agency which gives more detailed information in that specific property is provided in the table as reference, which has to be explored separately.

TABLE 2.2 PHYSICAL PROPERTIES OF CHLORINE

Parameter	Value	Reference
Chemical formula	Cl_2	
Melting Point:	-150 ° F	(EPA, 1998)
Vapour Pressure:	7600 mm Hg at 86.0 ° F	(EPA, 1998)
Vapour Density (Relative to Air):	2.49	(EPA, 1998)
Specific Gravity:	1.424 at 59.0 ° F	(USCG, 1999)
Boiling Point: Boiling Point:	-30.3 ° F at 760.0 mm Hg	(EPA, 1998)
Molecular Weight:	70.91	(EPA, 1998)
Water Solubility:	0.7 %	(NIOSH, 2003)

2.7 RISKS AND MODELS

In Indian conditions, the clean fuel, Liquefied petroleum gas (LPG) is used for 75% of the domestic cooking or commercial cooking rather than a material used in the industries [35]. It is marketed in India as per the specifications approved by the (BIS 4576:1999) code[36]. LPG is transported from import terminals or petroleum refineries or natural gas fractionation plants to the bottling plants through road, railway or pipelines. Bullet tanker or bulk LPG Tank Truck (TT) is used to transport it through road. Bulk LPG wagons are used in the railways.

The LPG TTs are made as per BIS 2825: 1969 code [37] in India. The tanks are manufactured with three internal baffles, each baffle having a radius of 3m using stainless steel (SS) with a minimum corrosion allowance of 0.5 mm and painted with two coats of white enamel paint as per BIS 9618: 1980 code [38] and OISD-159: 2002 guidelines[39] . The design pressure is 15.5 bar with walls of 4mm and the ends of 6mm. The tanks are with 457 mm diameter manhole. The diameter of drain, vapour line connection and connection pressure gauge is 48 mm. Liquid inlet/outlet is 51mm. Diameter of its fixed level gauge is 6.25 mm and rotogauge is 25 mm. On the loading and unloading pipes at the top and bottom of the tank, two safety valves each of 50 mm diameter are installed. [40]. Usually the LPG temperature is kept slightly below -40^{0}C and the pressure below 1 bar.

The characteristics of LPG supplied by different oil and gas companies may vary slightly but they have to follow the vapor pressure and volatility standards given by (BIS 4576:1999)[36].

Even though non- toxic, odor-less and non-corrosive liquid, LPG is highly flammable and when released in the atmosphere can cause severe hazards. Auto ignition temperature of LPG is in between 4100C to 580^{0}C and boiling point is in between -20^{0}C to -27^{0}C. Heating value of LPG is around 50MJ/kg. Its LFL is 1.8% (v/v of gas in air) and UFL is 9.8% (v/v of gas in air). Its LEL is 1.8% (v/v of gas in air) and UEL is 9.8% (v/v of gas in air). Since the LEL and UEL are very narrow, it is very hazardous, especially in presence of an ignition source.

While transporting LPG through road, due to any reason if the TT has a leak and gas is released from a pressurised TT, vapour clouds can be formed. This can cause subsequent fire and explosion in the presence of an ignition source. In the present study, case studies of TT accident carrying LPG as well as Chlorine gas has been analysed in detail using ALOHA (Area Locations of Hazardous Atmospheres) simulation codes.[29]

Many models and attempts were made for the analysis of LPG TT accidents. In an accident analysis Bubbico et al [41] assumed 80% fill of the full capacity for LPG tankers. But accident during an LPG tank filling activity, Bubbico and Marchini [42] analysed using 65% of tank LPG capacity. A road accident involving a tanker transporting LNG was analysed by Planas et al [43] with an initial fire and a BLEVE. The risk analysis of LPG vehicles in the enclosed car parks, done by Schoor et al [44] found the mass fraction of released vapour . Crowl and Louvar [45] used TNT equivalency method to calculate the effect of explosion .

A container filled with a flammable liquid leading to boiling liquid expanding vapour explosion (BLEVE) after generating fireball was experimented by [46] Lees. The development of the fireball and the associated colour changes to white, yellowish, - orange or light red and the relationship with the maximum temperature and effective flame temperature was discussed by Lees. [47]. The ignition studies on hydrocarbon fuels only lead to the solid flame model, describes Demichela et al [48] .

Many models are available for analysis. For example, the solid flame model by Roberts [49] which is used in the ALOHA considered for this study is slightly varying from the point source flame radiation model suggested by Pieterson and Huaerta. [50]

As per the reports of Kumar [51], OISD [52] loss and damage in the LPG accident at Chala, Kannur, most of the victims of the accident were in the vicinity of the National Highway, in an area bounded by 150 to 200 m of the accident site in all directions. More than 50 vehicles were damaged, glass windows of many houses cracked or broken and the outside walls many houses in the vicinity were cracked or collapsed because of the impact and shock waves [40]. The reported findings in the above are at par with the analysis made in this study also. In these reports the rupture of the tank is initiated by a leak through a small hole in the tanker developed due to the accident. The gas release and subsequent pressure conditions was extensively used for the analysis. Further to that, the relationship with the last known speed of the vehicle which is causing the accident and the actual measured values of the hole sizes developed in the tank body is explored in this study. This is based on the data available from various TT incidents as well as traffic records.

The backbone of this research is developed from the information available through this literature. The gap in each model or in each experiment is identified and used for developing the current model. Limitations of the researcher also is identified from this journal information.

2.8 CHAPTER SUMMARY

The relevance of the broad area of Quantitative Risk Assessment and how tools in QRA are relevant for this research is explained based on the literature. The explanations for the various conditions of the road and road features, various accident studies conducted, the details of the hazardous materials like LPG and chlorine used for the research, various risks involved in the transportation processes, different accident analysis models available and how the researchers utilised them is also explored.

CHAPTER 3
ROAD ACCIDENT ANALYSIS IN GENERAL AND CONTROL OF ROOT CAUSE

3.1 OVERVIEW

Kerala being a densely populated state undergoes a number of road accidents every year. This chapter is intended to analyse the accident data for a number of years. The data available from Kerala police and national Highway authority is analysed in detail. The causative factors are explained. The accident data in general and the accidents involved with the hazardous materials in specific is analysed.

3.2 ANALYSIS OF ACCIDENT DATA IN KERALA

The number of road accidents is increasing in Kerala. Kerala Police[27] revealed that in the year 2013, 4258 persons were killed, 40346 persons got injured and 1675 persons escaped without any injury through 35215 reported road accident cases. Poor design and condition of the road, increased vehicle density and vehicle population, over speeding, rash and negligence in driving, violation of the rules and regulations, improper condition of the vehicles, changes in climate etc. are some of the major reasons for the accidents resulting in the high mortality rate. The basic engineering design of the road and improving the conditions of the road are addressed in the transportation design stage. Improving the conditions of the road either in the navigation or in the control through technology belongs to the Information Communication Technology (ICT).

The number of deaths in various years is shown in Fig. 3.1. The number of reported accident cases and the number of persons injured in the accidents for the years 2011 to 2013 are[53-58] provided in Fig. 3.2.

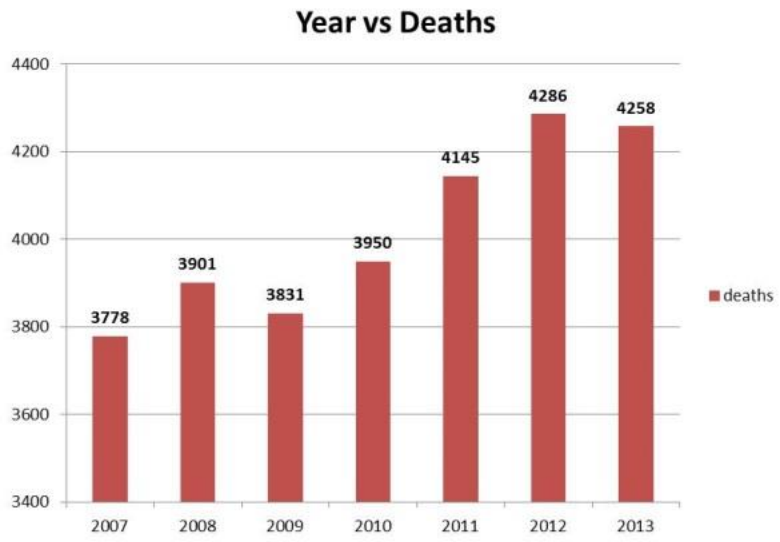

Figure 3.1 Deaths in various years

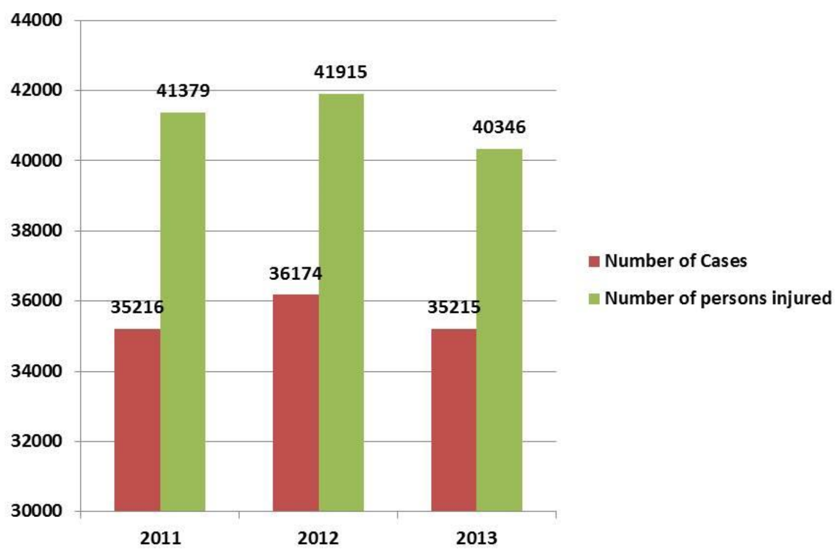

Figure 3.2 Road accident statistics

There was a 2.79% increase in road accidents in 2012 while there was decline of 2.69% in the year 2013. [54] The reduction is because of massive safety awareness campaigns and intensive law enforcement through Information Communication Technology (ICT). [55]

The implementation of ICT aids started from April 2013 intensively, and thereafter except in the immediate month May, there was a significant reduction in the number of accidents, number of injured persons and number of persons killed in road accidents. Until May, the trend was ascending, but even in the rainy month of June, the trend started descending owing to the reasons of strict law enforcement. The percentage reduction in accidents comparing to the previous year in June (5.37%), July (8.88%), August (5.36%), September (7.83%), October (7.84%), November (6.75%) and December (2.19%) is evident from the Fig.3.3. [56]

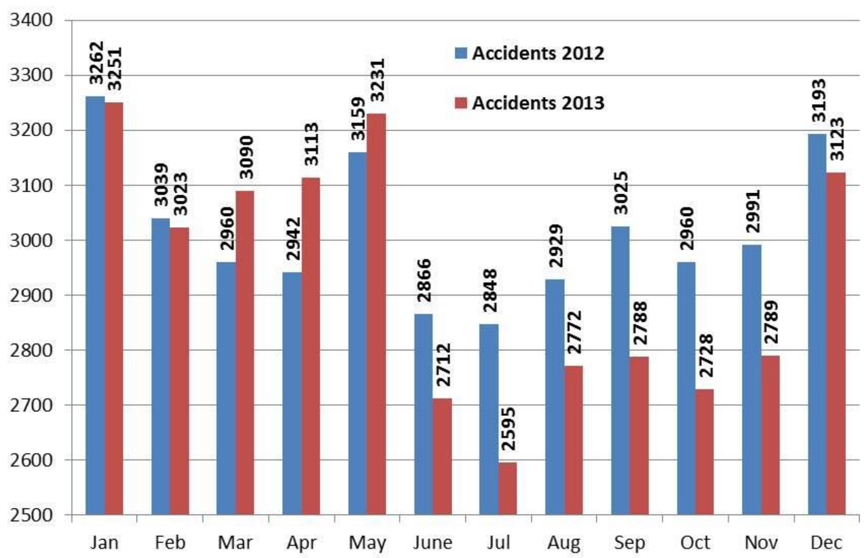

Figure 3.3 Number of accidents in various months

The number of persons killed due to the reasons related to driving in road accidents in the year 2012 was increased by 5.64% than the previous year but decreased by 2.48% in 2013 as in Fig. 3.4 to 3.6. [57-58]

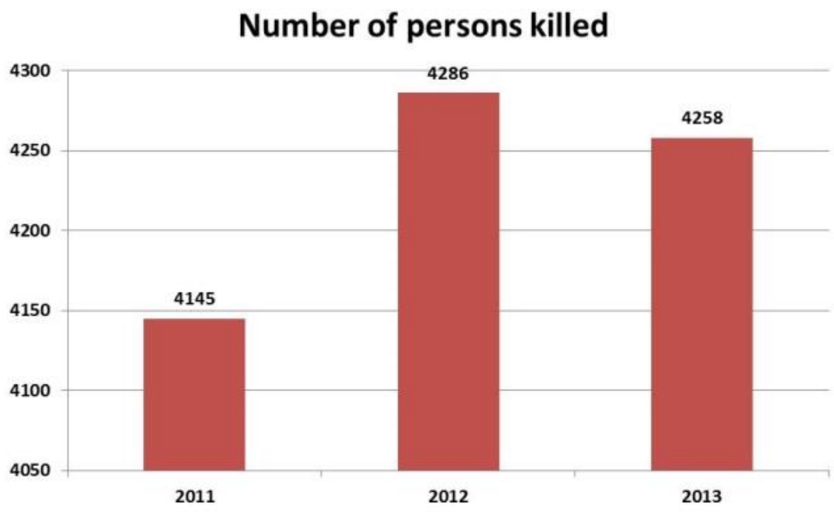

Figure 3.4 Number of persons killed due to reasons related to driving

At the same time, the percentage reduction in the number of accidents happened during the year 2013 is 2.68, bringing the number back almost to the same as in year 2011. This is a significant achievement when we consider the average annual increase in the number of motor vehicles in Kerala is 4%.

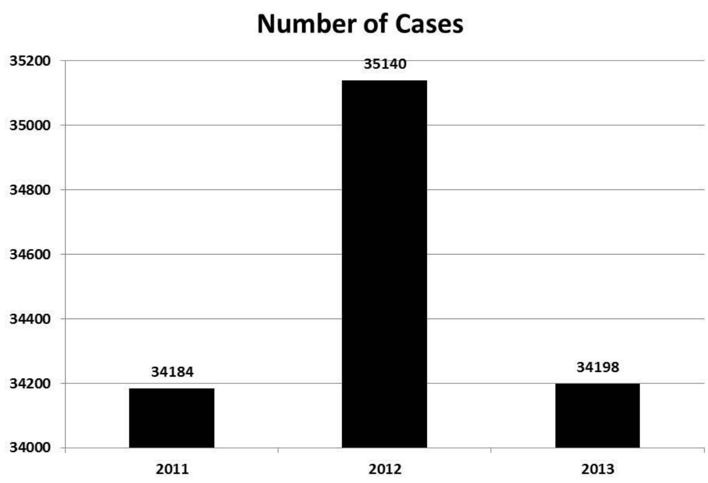

Figure 3.5 Fault of Driver

The decline in the total number of deaths due to road accidents was only 0.65% for the year 2013, while the decline in the total number of accidents was 2.19%, which is significant.

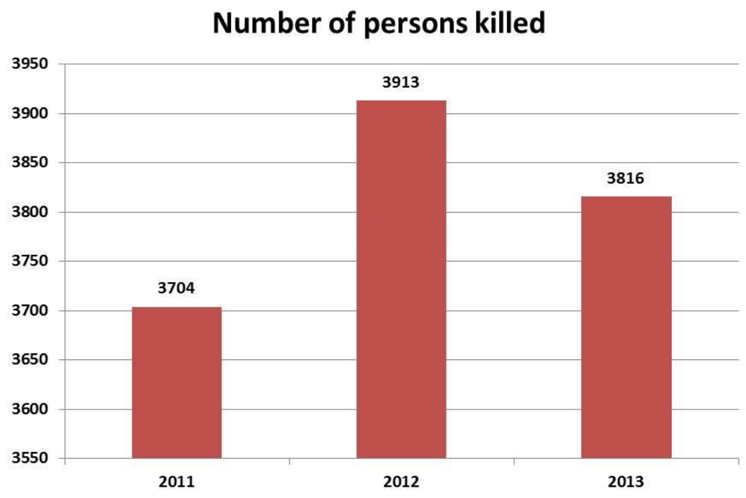

Figure 3.6 Persons killed by fault due to driver

Intoxicated driving was a major reason behind many of the accidents. The reported cases of number of accidents due to drunken driving are comparatively less, to the tune of 0.28% in 2011, 0.46% in 2012 and 0.08% in 2013 of total number of accidents in the respective years. But the measures to prevent it before entering into an accident through breath analyzers was highly effective as the drastic reduction in the number of cases reported in 2013 as in Fig.3.7. The increase of accidents due to drunken driving in 2012 was 66% comparing to 2011 while it was decreased by 83% in 2013 comparing to 2012 and 72% comparing to 2011.

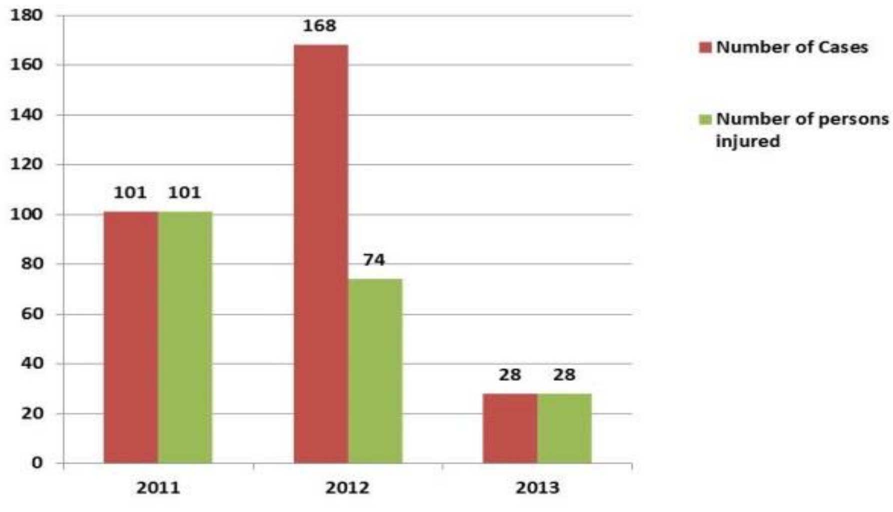

Figure 3.7 Cases due to Drunken Driving

Even though the decrease in deaths is only nominal, the number of accidents as well as number of killed persons are decreased drastically as in Fig. 3.7 and 3.8. [53-58] The reduction in the total number is a positive sign that the enforcement measures are becoming fruitful.

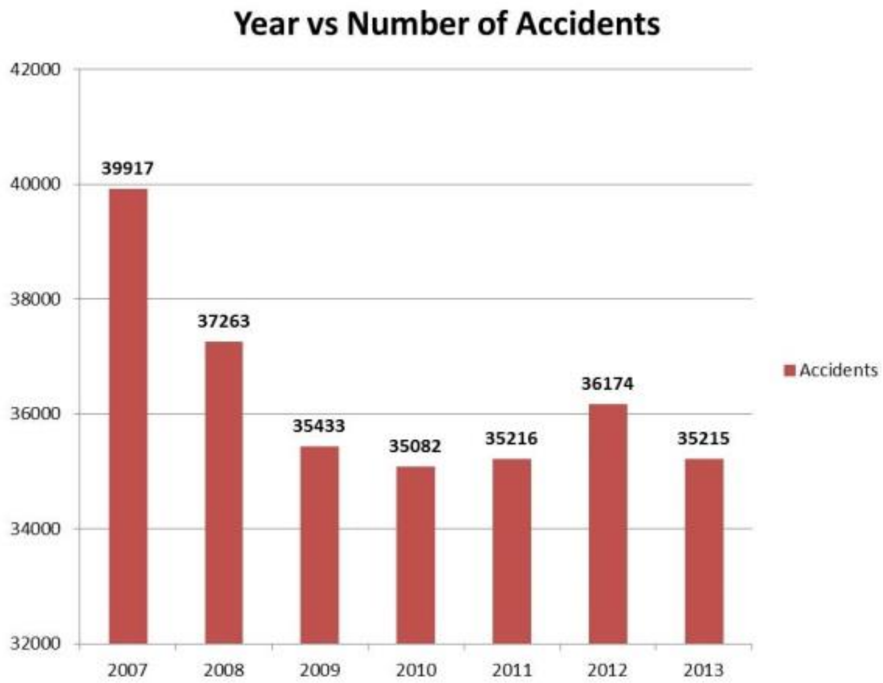

Figure 3.8 Number of accidents in various years

Other than this, the number of traffic law violations recorded by the camera surveillance mechanism at some points is also a positive indication. The data is not available for all the camera locations, but the revelations of the available data are justifying the effectiveness of ICT based enforcement measures.

3.3 GENERAL ROAD ACCIDENTS

Other than the general Kerala statistics, based on the accident data collected from three different stretches of National Highways in Kerala, the nature of accidents was analysed. Details of the accident data collection points are provided in Table 3.1.

The nature of accidents was classified as Overturning, Head on Collision, Rear End Collision, Side Wipe, Right Turn Collision and Skidding and the percentages of each category in the respective sections are given in Fig.3.9 to Fig. 3.11. A comparison of the nature of accidents[59] in all the three sections is given in Fig. 3.12.

TABLE 3.1 ACCIDENT DATA

Road	**National Highway 544 (Old NH47)**	
Period	**21.06.2014 to 26.07.2015**	
Road Section	**Study Area Location**	**Number of accidents**
1	Walayar-Vadakkancherry	74
2	Vadakkancherry - Thrissur	89
3	Thrissur- Angamaly	82

Head on collision is the dominant factor in Highway Section 1 and 3, while rear end collision is dominant in Section 2. Comparing all the three sections, it is evident that the collision from front or back (head on collision as well as rear end collision) is the major factor (65%, 76% and 59% respectively).[54]

The root cause of the accident has to be understood for taking any control measures. Driving the vehicle in an intoxicated condition either by the influence of alcohol or some alternatives, Over speeding of the vehicles, Vehicle going out of control due to various reasons, Various faults (such as faults of the driver of the vehicle, faults of the driver of the other vehicle, unpredicted sudden movements of the cyclists, unpredicted movement of the pedestrians, unpredicted actions of the passengers), Defects in the mechanical condition of the road or the vehicle are some of them.

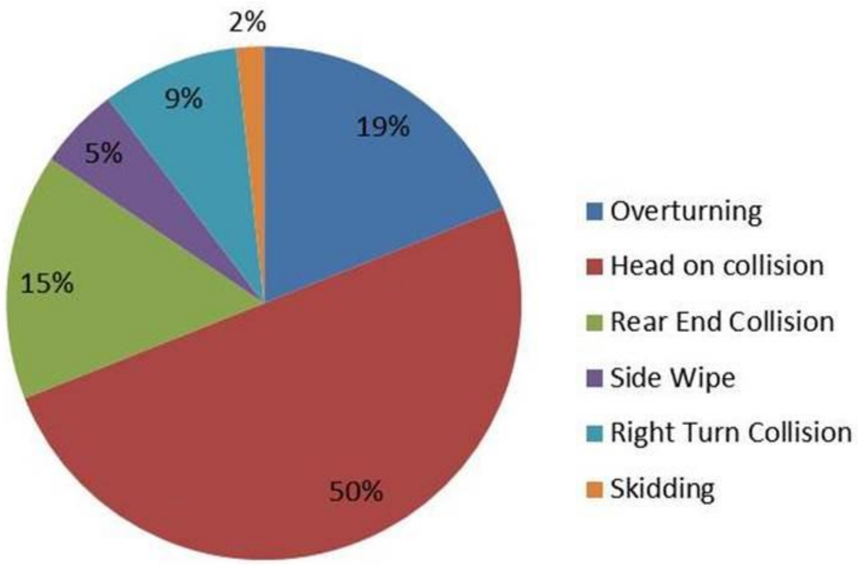

Figure 3.9. Nature of accidents in Study area section 1

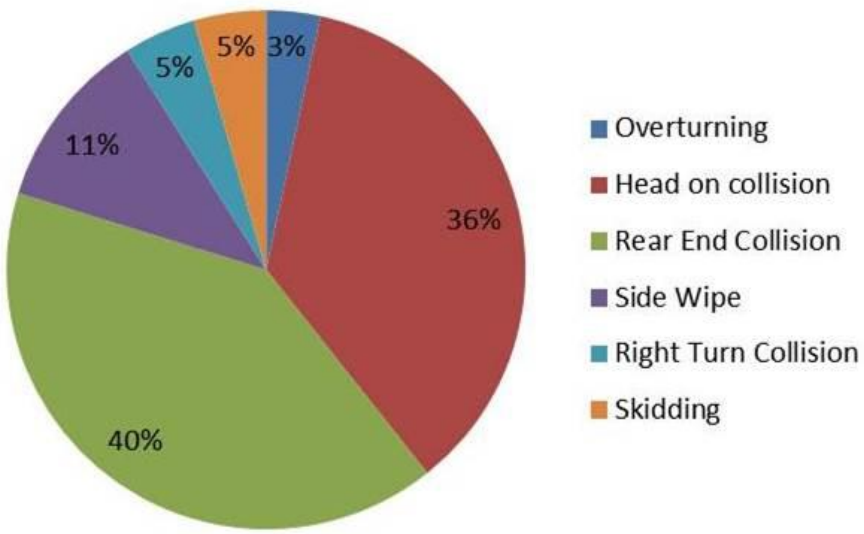

Figure 3.10. Nature of accidents in Study area section 2

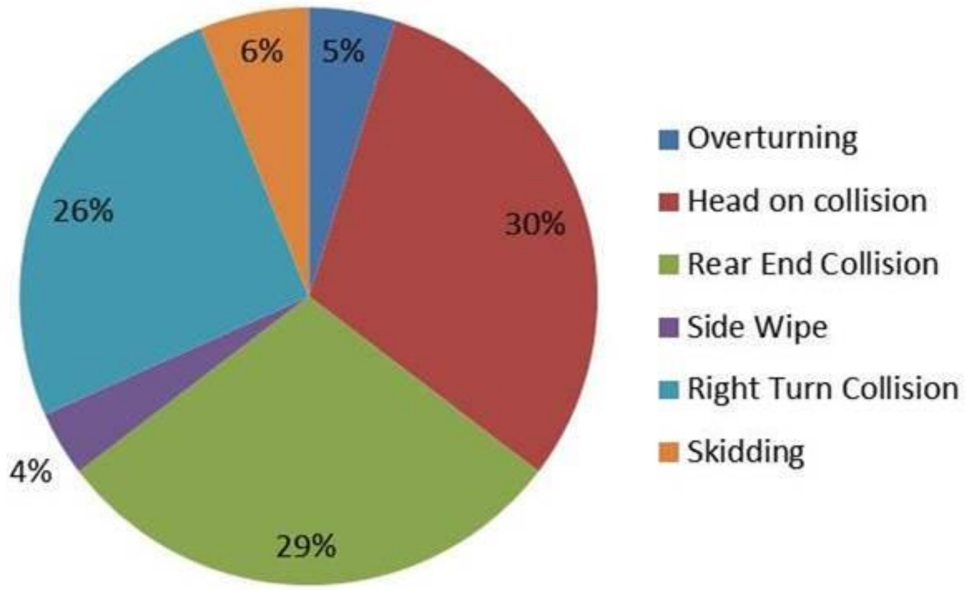

Figure 3.11. Nature of accidents in Study Area Section 3

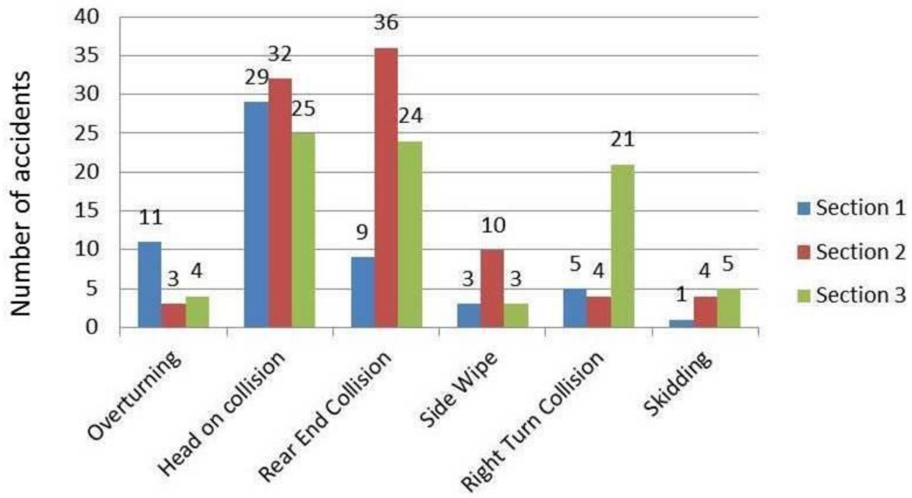

Figure 3.12. Nature of accidents in all sections of Study Area

The percentage contribution of these causes are given in Fig. 3.13, Fig. 3.14, Fig. 3.15 and a comparison is given in Fig. 3.16.

The overall contribution of the over speeding to cause accidents are 74%, 33% and 56% in the respective sections, emphasizing the featured characteristics of the accidents on roads by Asha [16]. Here also, in the studied cases 53.06% of the accidents are because of over speeding.

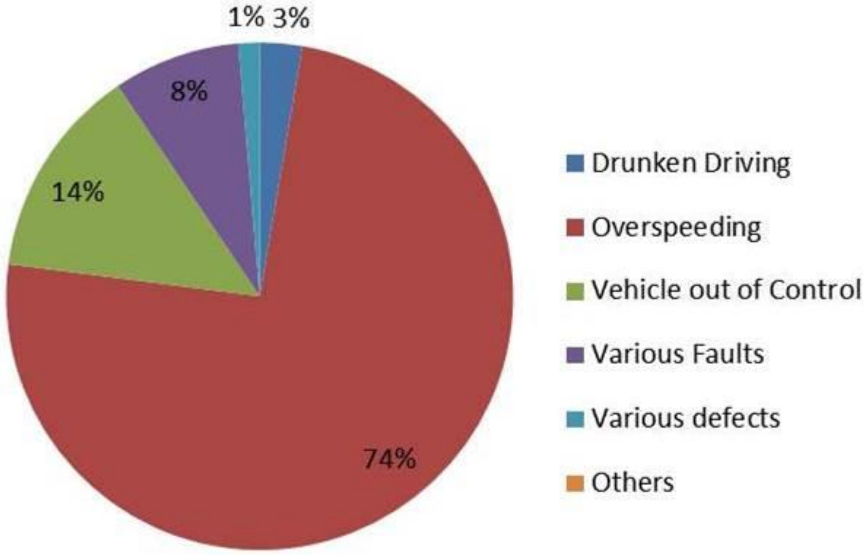

Figure 3.13. Causes of accidents in Study Area Section 1

The features of the road have great influence in the development of an incident into accident. The characteristics of the flow highly influences in resulting accidents depending on the road profile. The accident cases with the road profile as single lane, two lane, three or more lanes without median and three or more lanes with median are compared in Fig. 3.17. The general trend indicates more number of accidents in two lane road where the lanes are not separated with medians.

The condition of the road and its geometry either in the vertical plane or in the horizontal plane contributes much. The comparative analysis of the accidents happened in Straight road, Road with slight curve, Road with sharp curve, Flat road and Road with a gentle incline are compared in Fig. 3.18. The numerals indicate the fact that drivers take more care in sharp curves comparing to the slight curves. Indirectly the chances of accidents are more in a slight curve than a sharp curve because the slight curve seems to be nominal deviation from the continuity of straight line psychologically, resulting in the accidents. [53-58]

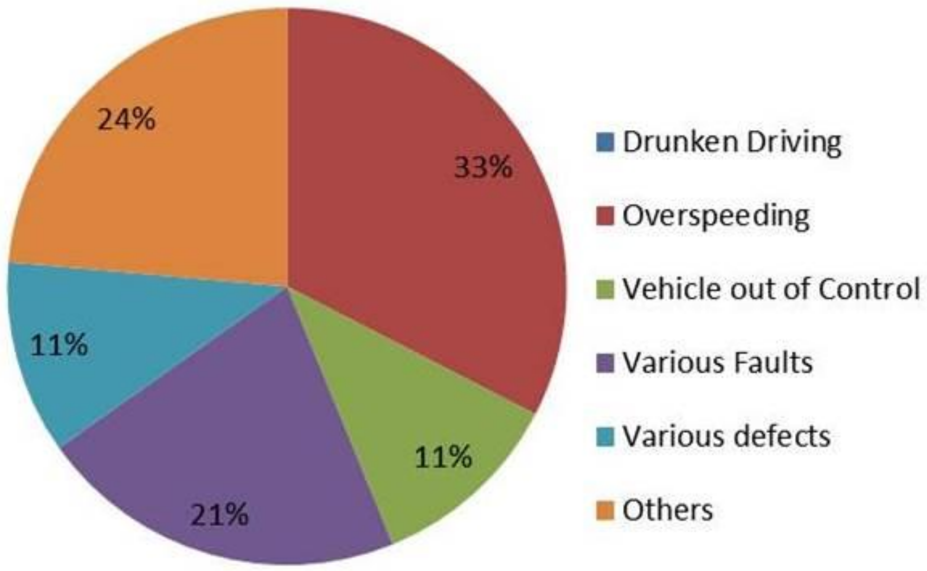

Figure 3.14. Causes of accidents in Study Area Section 2

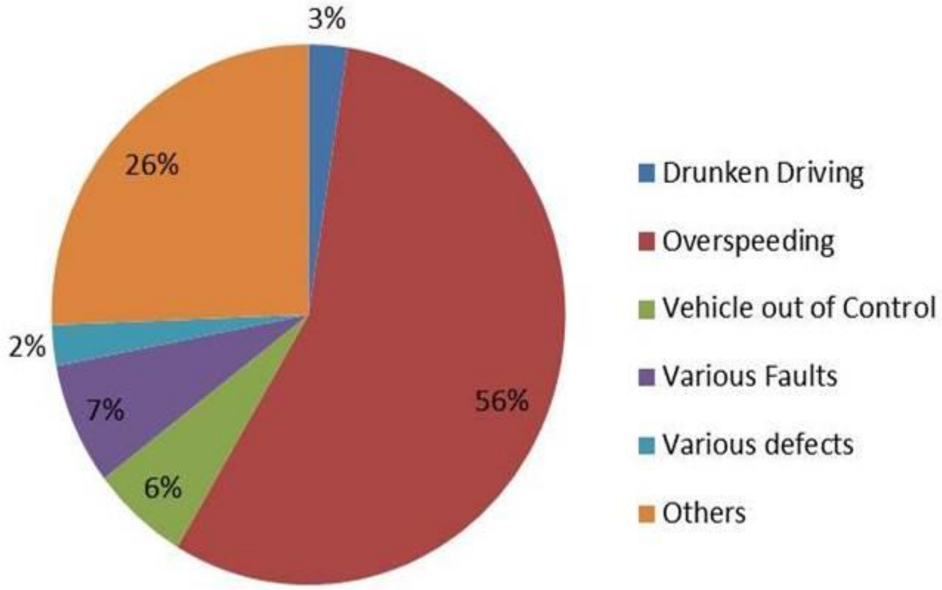

Figure 3.15. Causes of accidents in Study Area Section 3

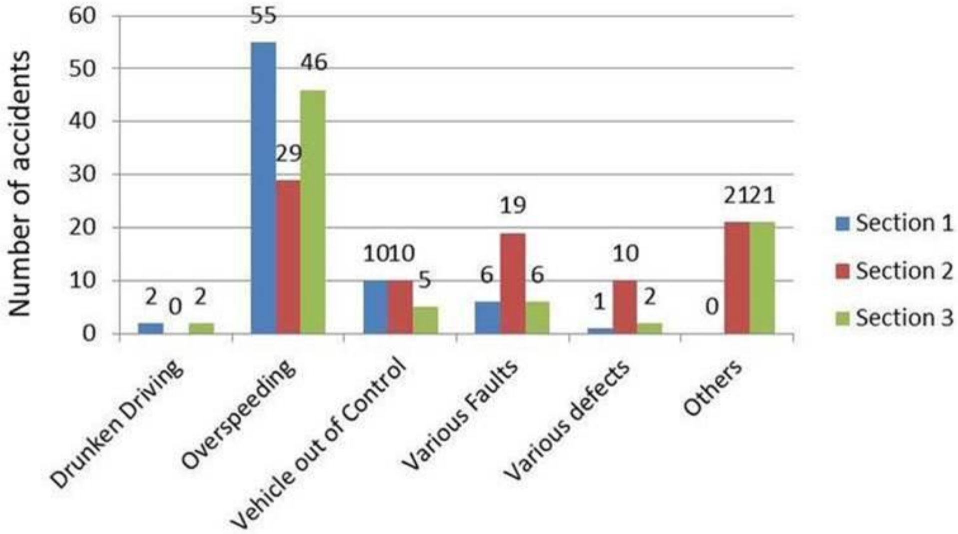

Figure 3.16. Causes of accidents in all sections of study Area

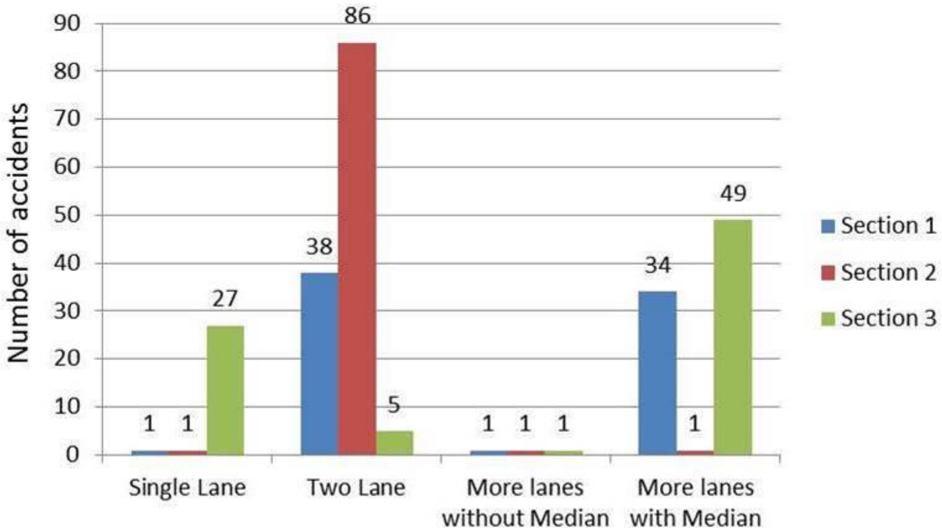

Figure 3.17. Accident Analysis based on Road Condition

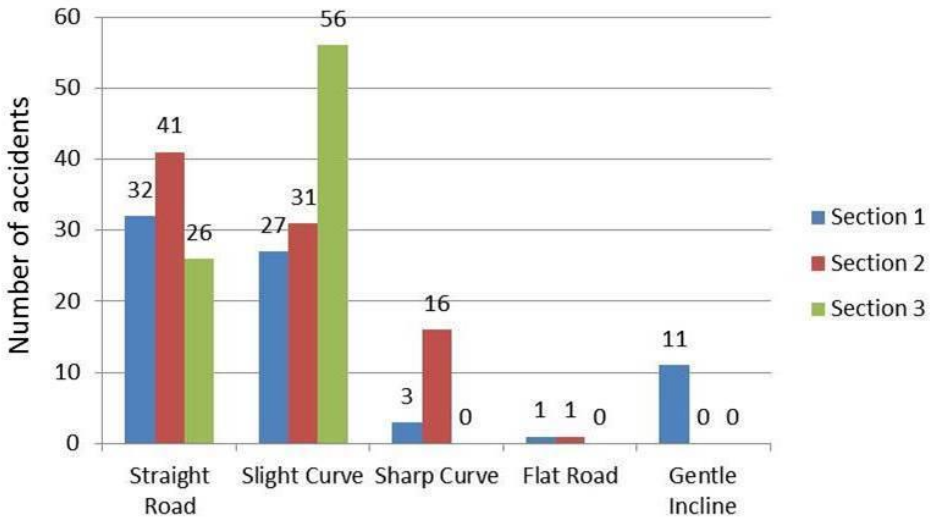

Figure 3.18. Accident Analysis based on Road Geometry

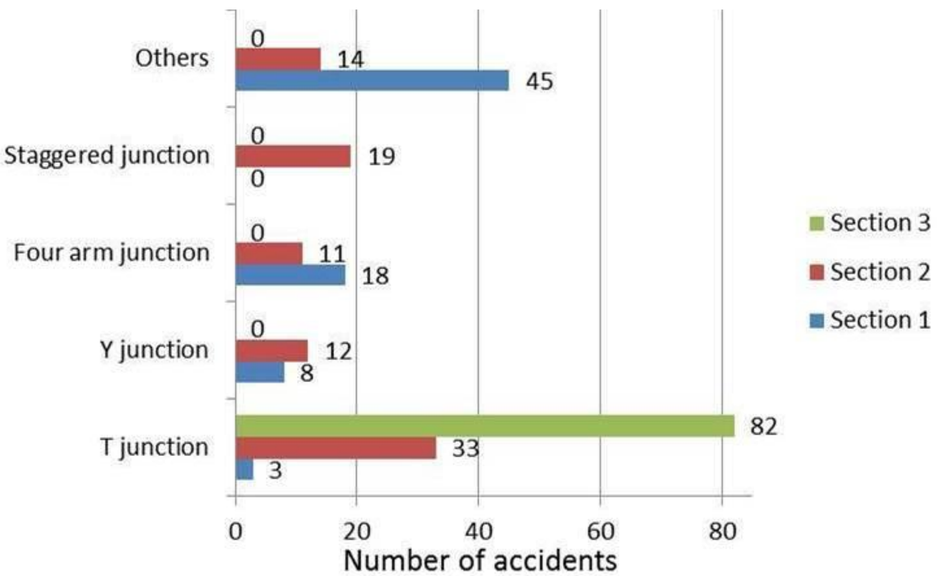

Figure 3.19. Accident Analysis based on Road Intersection Type

The road intersection type and the entry, such as T junction, Y junction, four arm junctions, staggered junction and other types including the roundabouts are shown in Fig. 3.19. More number of accidents is indicated in the T junctions because of the increased number of conflict points at the time of entry or exit from the junction. [59-65]

3.4 ACCIDENTS WITH HAZARDOUS MATERIAL TRANSPORTATION

The accident data used in the above analysis does not make any specific mention about the hazardous material transportation and the involvement of such materials in accidents. So secondary sources were selected to identify such accidents in Kerala. Instead of the specific stretch selected, entire Kerala state was selected as the site for data collection.

A serious accident involving the hazardous materials transportation was reported on December 31, 2009, in which seven people lost their lives when the LPG transported in a tanker exploded at Karunagapally in Kollam district [60].

Next serious accident was on August 27, 2012 in which an LPG carrier had burst into flames at Chala in Kannur district, [61-65] killing 20 persons and injuring many. A similar incident reported on January 7, 2014, near Angamaly, Ernakulam in which a gas leak in an LPG tanker on the National Highway triggered panic among the local people.

Also on January 14, 2014, at Kalliasseri in Kannur a bullet tanker lorry carrying 18 tons of LPG overturned and caught fire on the National Highway in the early morning hours, forcing residents in the area to run away from their homes in panic. But because of the preparedness of the people from the Chala incident reduced the severity, and made the life loss to zero. [61-65] The existing highway which does not have proper geometrics, including smooth curves, resulted in the incident. The vehicle density expressed in average passenger car unit (PCU) counted on a two lane NH here in this region is 40,000, theoretically only a four-lane road can cope with that rate of vehicle density. [61-65]

Generally, in a bullet tanker, the LPG is filled and transported as "liquid under high pressure". On accidental release, it quickly vaporises into highly combustible gas which can catch fire or explode. Most gas leaks and explosions are caused by damage to the valves that control the flow of LPG from the tanker. The heavily populated areas along the sides of the National Highway in Kerala enhance the vulnerability factor. It is very difficult to contain the leaking gas except with specialised equipment. The State Disaster Management Authority (SDMA) has identified that large parts of the state are considered vulnerable to the hazards of LPG tanker accidents. The State has only one specialised emergency rescue vehicle based in Ernakulam, equipped to plug an LPG leak or transfer gas from a stricken tanker, or to manage other chemical accidents.[61]

Comparing to the general road accident cases, the accidents with HazMat is also similar in happening, when we consider the initial part. But the severity of the accident is increasing just after the accident due to the release of hazardous chemicals and its consequence.

Based on the general road accident data, many accident causation models were suggested. In these accident causation models, the framework of accident description starts with the Driver-Vehicle-Environment model (DVE model) which is the most accepted one. In the functional point of view, the DVE system processes were explained through Human Functional Failure (HFF) model. Later, 'On The Spot' (OTS) model was suggested. In all these models, various parameters as we discussed in the accident scenario only was considered. The causative factors during hazardous material transportation was not specifically mentioned in these models. Establishing a link between the two models, general accident causation model of hazardous materials and accident causation model of transportation systems is the need of the hour.

3.5 CHAPTER SUMMARY

Accident data relevant to Kerala conditions available for a number of years is examined along with the causative factors in this chapter. While examining the causative factors, the location specific characteristics also were examined in detail.

CHAPTER 4
QUANTITATIVE RISK ASSESSMENT

4.1 OVERVIEW

This chapter discusses the overall processes of QRA in the road accident sector. The methodology of QRA, various types of risks, analysis of the risks while transporting chlorine and LPG through the road, significance of the risks and impact on the society, a correlation model linking the road features and hazardous material, limitations of the model and the validity of the model is explained.

4.2 QRA METHODOLOGY

Risk is defined as a function of hazard, hazard frequency and hazard consequences.

QRA start with identifying accident scenarios, and Risk is presented generally as any of the following:

a. **Location specific individual risk (LSIR)**: Location specific individual risk provides a measure of hazard associated with different geographic locations within a facility. The assumption is that each target location is permanently inhabited by a single individual. The calculated risks are given as risk contours.

b. **Individual risk (IR):** This is determined on a case to case basis for each individual working in a facility. The contribution of individual risk is evaluated as a time weighted average of the LSIR values at each locations at which the work group will be exposed.

c. **Cumulative frequency Vs. Number of fatalities (F-N):** F-N curve also called societal risk is a plot of the cumulative frequency of events resulting in N or more fatalities against N. F will be a decreasing function of N.

The general accident data for Kerala State was collected for a few years. Then the causative factors behind the accidents were analysed. Overspeed being the main reason behind many accidents, the control measures of overspeeding through ICT was discussed in detail.

Other accident parameters related to Driver, Vehicle and Environment was analysed. Environmental factors and the Hazardous Material analysis was done with two chemicals, one flammable and the other one non-flammable. The flammable material is Liquefied Petroleum Gas (Butane) and the non-flammable material is Chlorine gas. The transportation of these materials under high pressure in liquid form in bullet tankers was considered. The identical incidents happened in the highway stretches were replicated with similar values to make the model. The analysis was done in ALOHA and plotting done with MARPLOT. Results were checked with the actuals. And potential directions in case of wind direction change also was analysed.
The second main reason behind the accident is the design condition of the roads. Intersection analysis was done for roundabout and signalised intersection using Sidra Intersection. The design details are furnished.

4.3 QRA OF LPG AND CHLORINE DURING TRANSPORTATION

Following section summarize a typical QRA study done during transportation of Liquefied Petroleum Gas (Butane) and Chlorine through the National Highway.

The Chemical details of LPG and Chlorine used for the simulation as per CAMEO is provided in the Literature Review section in detail. Various hazard scenarios were considered for the above chemicals, in three different places. Angamali in Ernakulam District, Chala and Kalliasseri in Kannur District.

4.3.1 CASE 1:

The chemical Chlorine was released through a hole of 1 cm diameter at the bottom of the tank, from a bullet tanker, after overturning from the road. The diameter of the tank was 1.8 m, length 6m, and the tank was containing around 4000 kg of chlorine under liquid condition under pressure. The ambient surrounding conditions were treated as urban and unsheltered single storied building with building air exchange rate of 0.62 per hour considered. The wind speed was 6mph from NE at a threshold height of 3 m from the ground and the humidity was 65%. The environment was partly cloudy with average outside temperature 88^{0}F. When the model was run as Heavy Gas, outdoor concentrations was 24.4 ppm and indoor concentration 6.36 ppm at a point 1 km W and 1 km S from the accident point. The spread is in Figure 4.1 and the toxic threat zone is given in Fig. 4.2

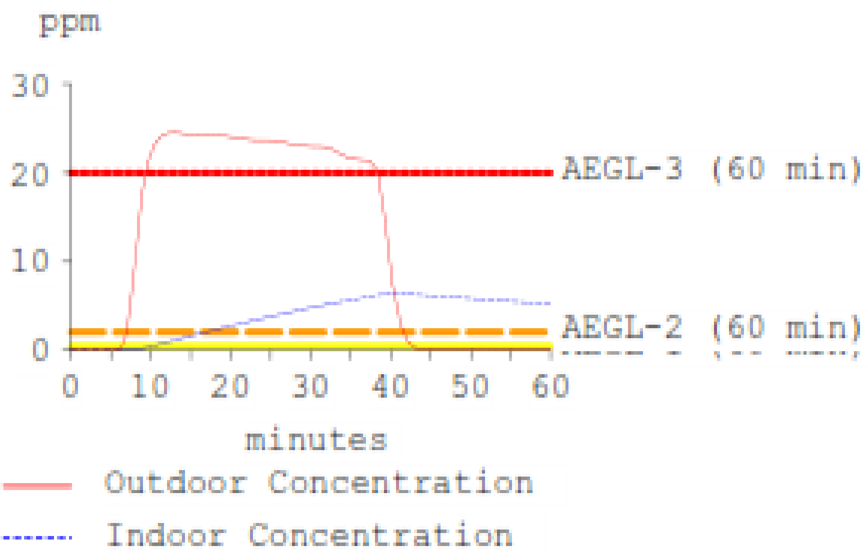

Figure 4.1 Spread of chemicals in 1 km distance

It is clear that red line (greater than 20ppm) is at 1.6 km and Orange line (greater than 2 ppm) is 6.1 km, and yellow line (greater than 0.5 ppm) more than 10 km, for first 60 minutes.

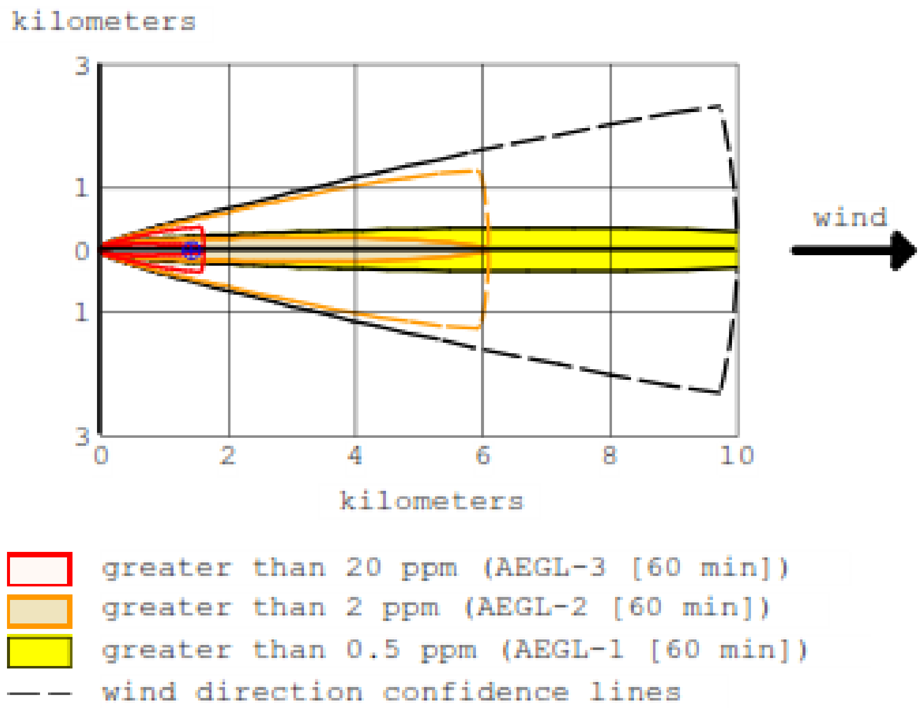

Figure 4.2 Toxic threat zone

4.3.2 CASE 2:

The LPG tanker accident at Chala, near Kannur in Kerala during midnight of 27 August 2012 was modeled using ALOHA. The accident occurred at National Highway connecting Kannur and Mangalore as indicated in Fig. 4.3.

The Chemical Liquefied Petroleum Gas (LPG) was released through a hole of 1 cm diameter at the bottom of the drain pipe in the tank, from a bullet tanker, after overturning from the road, subsequent to an attempt of overtaking. The internal radius of the tank was 3.0 m and the tank was containing around 16000 kg of LPG under liquid condition under pressure.

The ambient surrounding conditions were treated as urban and unsheltered single storied building with building air exchange rate of 0.62 per hour considered. The wind speed was 6 mph true at 315^0 at a threshold height of 3 m from the ground and the humidity was 65%. The environment was partly cloudy with average outside temperature 88^0F.

When the model was run Estimated Fire ball diameter for thermal radiation 5kW/m^2 is 457 m and 12.5kW/m^2 is 289 m and 37.5kW/m^2 is 156m in BLEVE (Boiling Liquid Expanding Vapour Explosion) condition as in Fig. 4.4.

After the explosion, a liquid jet fire developed which was modeled resulting in an affected distance of 60 m (for thermal radiation 5kW/m^2), 36m (for thermal radiation 12.5kW/m^2) and 12m (for thermal radiation 37.5kW/m^2) as in Fig. 4.5.

The affected area and influence zone arrived from the model is at par with the data collected from the accident site. Severity of the burns was more in the threshold zones as indicated in the above cases.

The model was run again for various sizes of openings, resulting in the release of LPG in varying quantities. The drain pipe hole size assumed were 2 cm, 3cm and 4 cm and the affected distance (Fig. 4.6a) and affected area (Fig. 4.6b) are plotted for different thermal radiation levels. It will give an indication of the zone in which rescue operations are to be started immediately.   These results are almost similar or exact as per the analysis done by Bariha N et al [66] in the paper "fire and explosion analysis: a case study from Kannur".

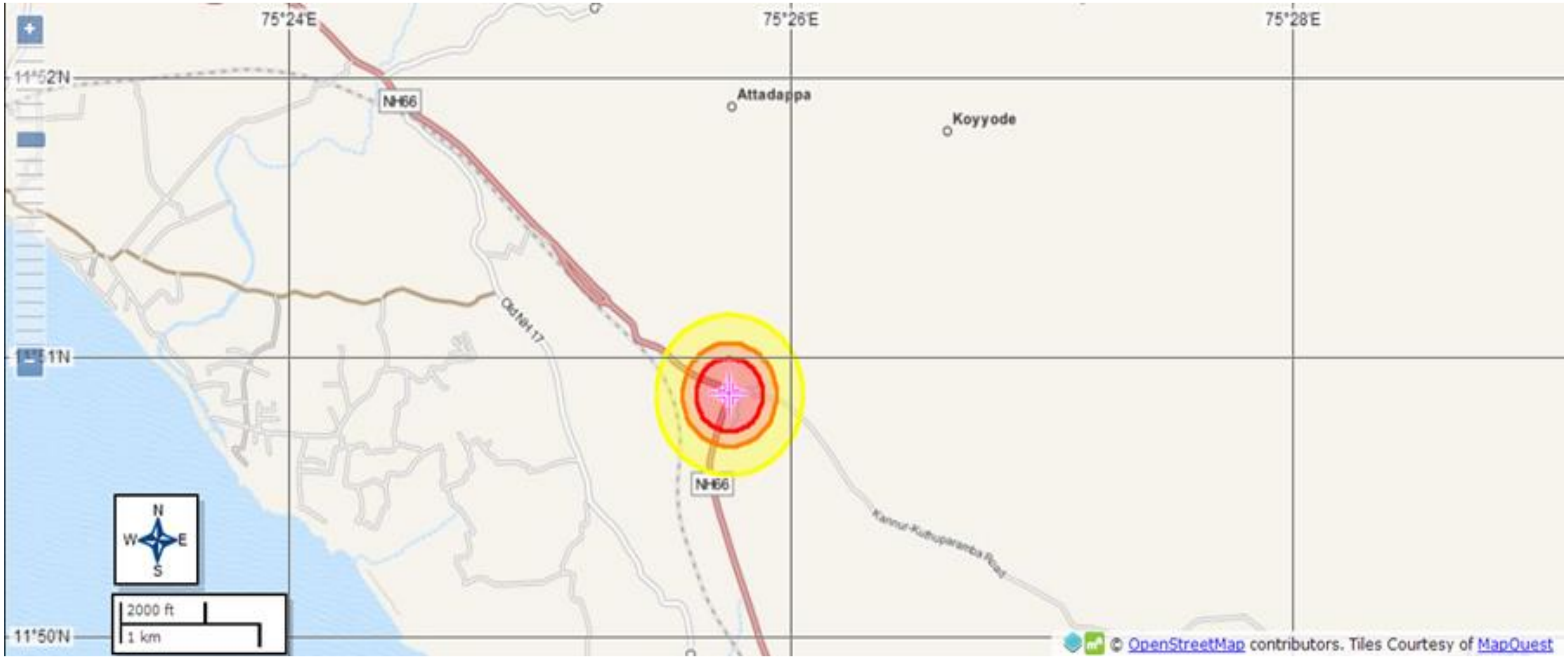

Figure 4.3 Chala BLEVE condition

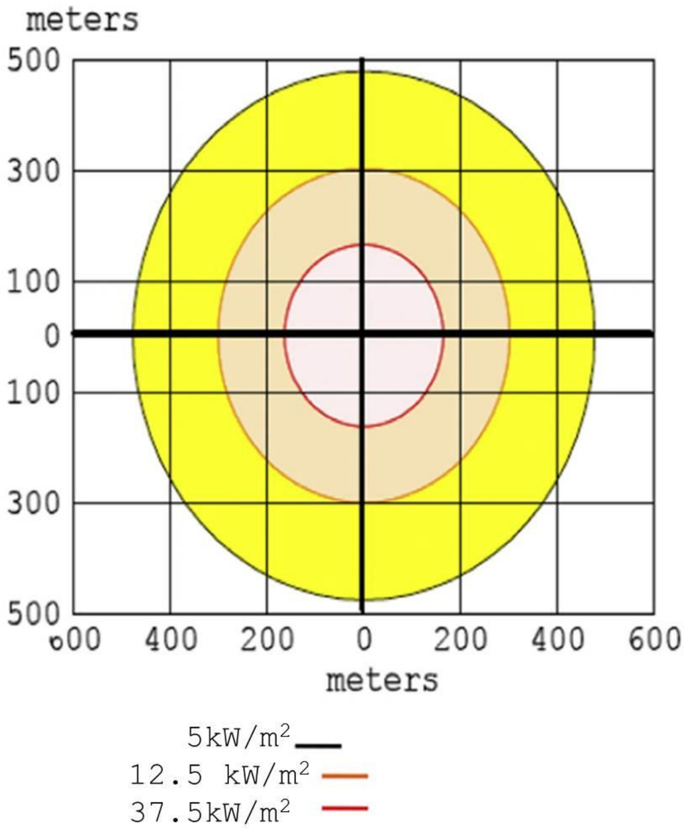

Figure 4.4 Estimated fireball diameter with various thermal radiation (Chala)

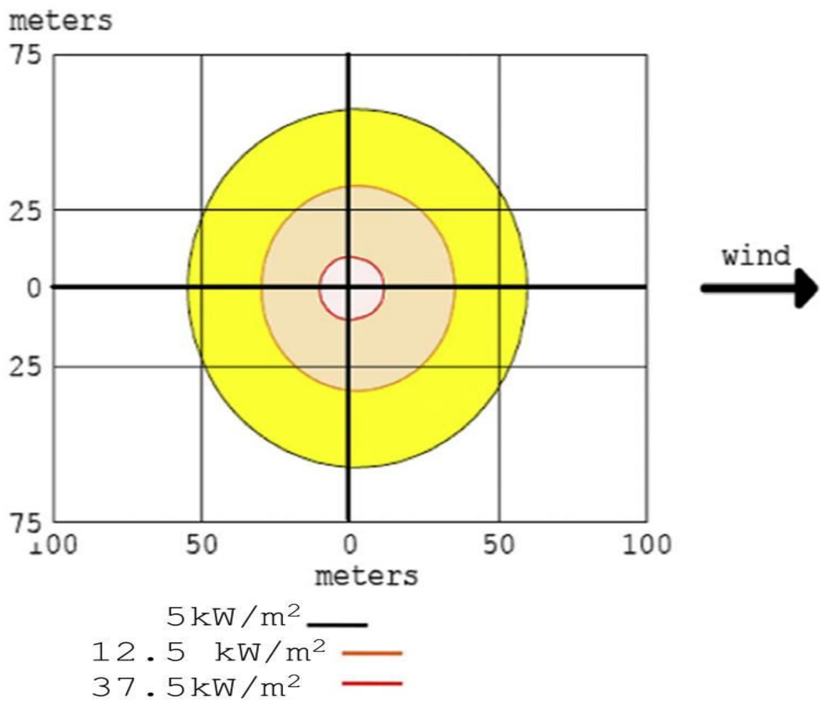

Figure 4.5 Estimated jet fire diameter at various thermal radiation (Chala)

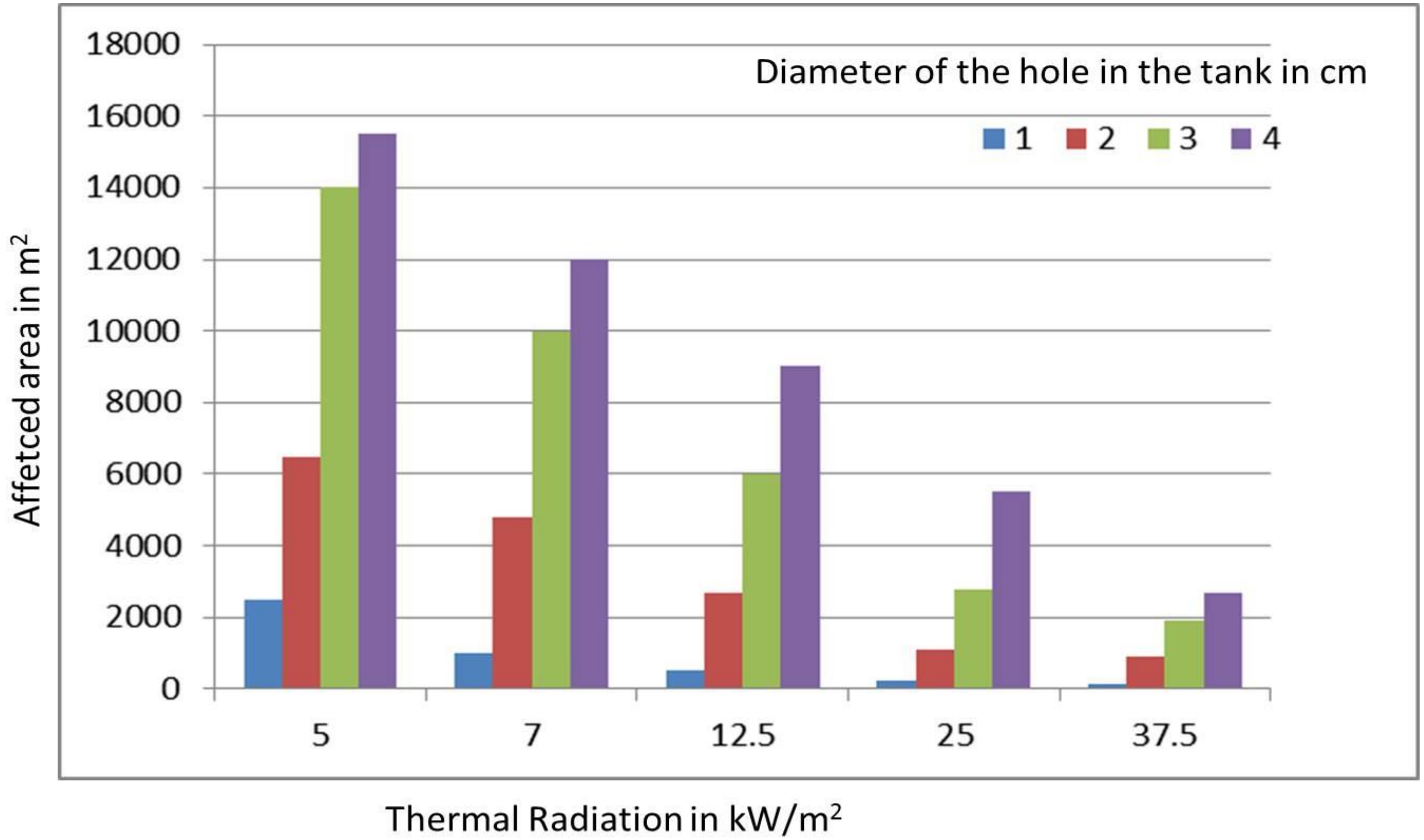

Figure 4.6a Affected area at various thermal radiation with varying hole sizes (Chala)

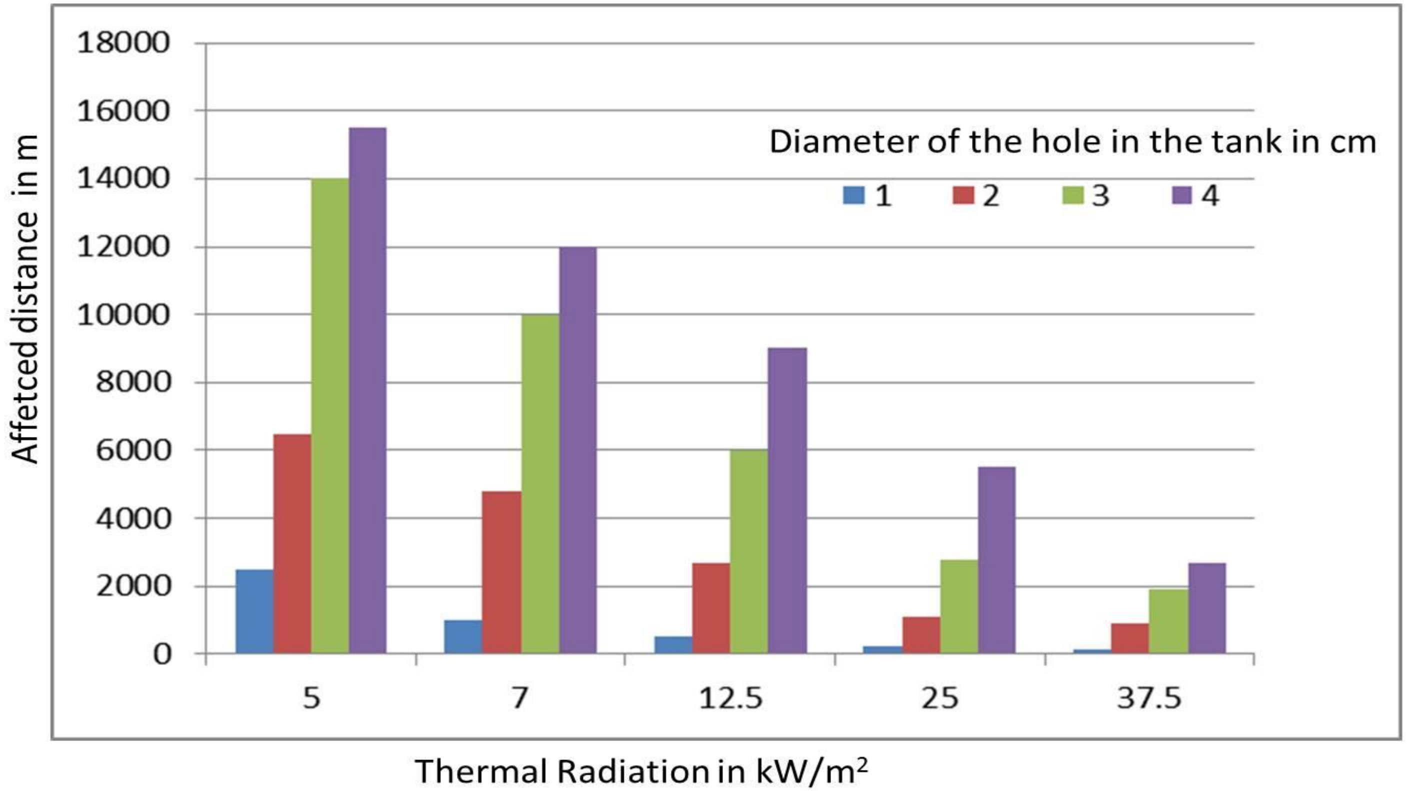

Figure 4.6b Affected distance at various thermal radiation with varying hole sizes (Chala)

4.3.3 CASE 3:

TABLE 4.1 TOXIC RELEASE AT ANGAMALI

Location	Angamali, India
Building Air Exchanges Per Hour	0.62 (unsheltered single storied)
Chemical Name:	LPG (Butane)
Molecular Weight:	58.12 g/mol
AEGL-1 (60 min) :	5500 ppm
AEGL-2 (60 min) :	17000 ppm
AEGL-3 (60 min) :	53000 ppm
LEL:	16000 ppm
UEL:	84000 ppm
Ambient Boiling Point:	-0.5° C
Vapor Pressure at Ambient Temperature:	greater than 1 atm
Ambient Saturation Concentration:	1,000,000 ppm or 100.0%
Wind:	6 miles/hour from 315° true at 3 meters
Ground Roughness:	urban or forest
Cloud Cover:	5 tenths
Air Temperature:	88° F
Relative Humidity:	65%
Source strength:	Leak from hole in horizontal cylindrical tank, Flammable chemical is burning as it escapes from tank, Tank Diameter: 1.8 meters, Tank Length: 6 meters , Tank Volume: 15.3 cubic meters , Tank contains liquid, Circular Opening Diameter: 1 centimeters
Chemical Mass in Tank:	6,814 kilogram
Tank	79% full ; Opening is 0 meters from tank bottom

Max Flame Length:	6 meters, Burn Duration limited to 1 hour
Max Burn Rate:	43.2 kilograms/min
Total Amount Burned:	2,563 kilograms
The chemical escaped from the tank and burned as a jet fire	

4.3.4 THREAT ZONE:

Threat Modeled as Thermal radiation from jet fire, as indicated in the Fig. 4.7.

Red : 10 meters --- (10.0 kW/m^2), potentially lethal within 60 sec

Orange: 11 meters --- (5.0 kW/m^2), 2nd degree burns within 60 sec

Yellow: 17 meters --- (2.0 kW/m^2), pain within 60 seconds.

Other details of various parameters and combinations of chemicals are provided in Fig. 4.7 to Fig. 4.20.

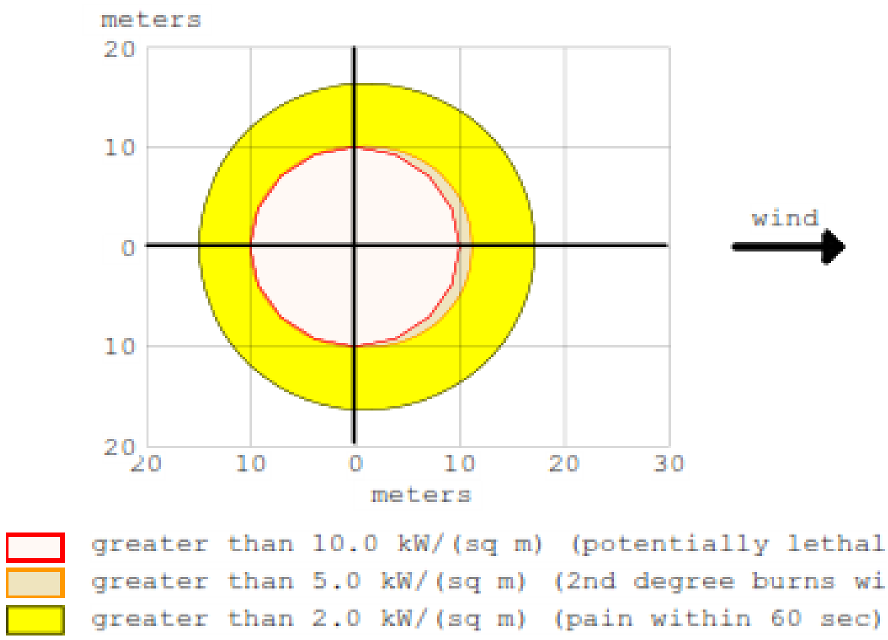

Figure 4.7 Immediate threat zones Angamali

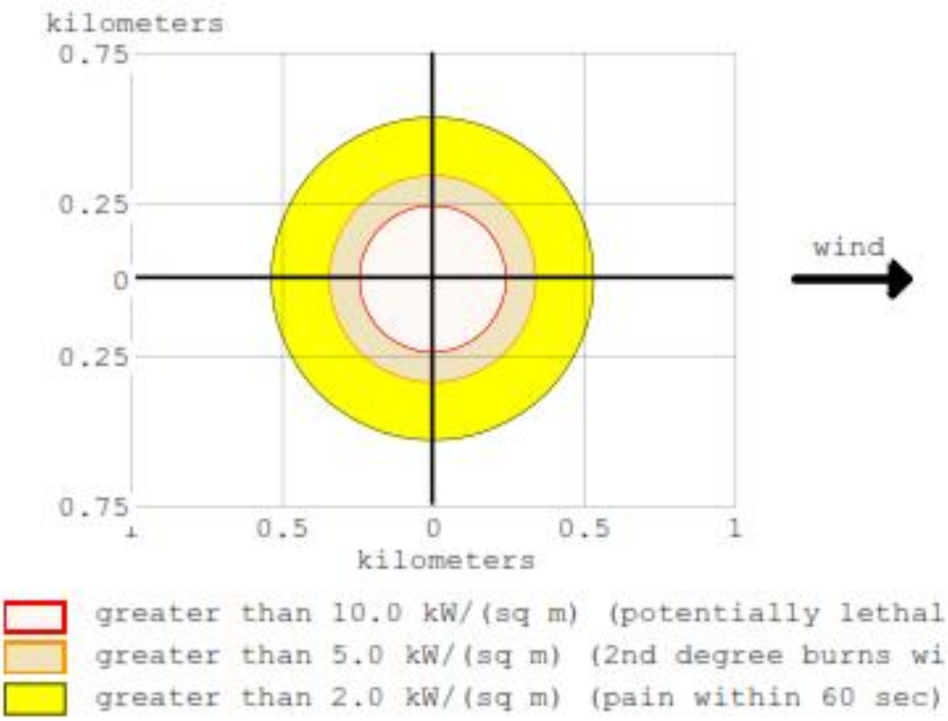

Figure 4.8 Thermal radiation Zones (Angamali)

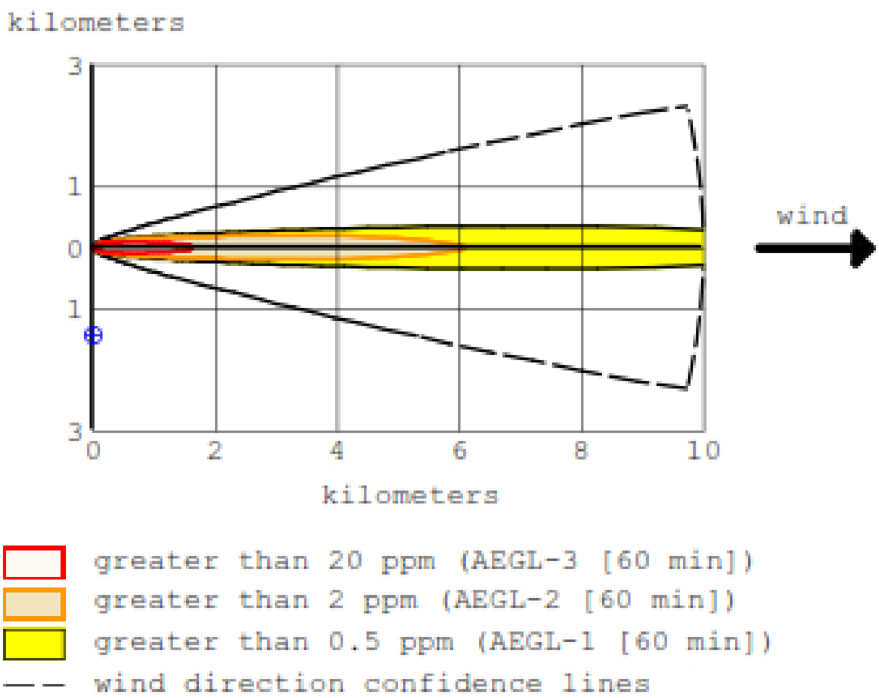

Figure 4.9 Spread of chemicals in surroundings (Angamali)

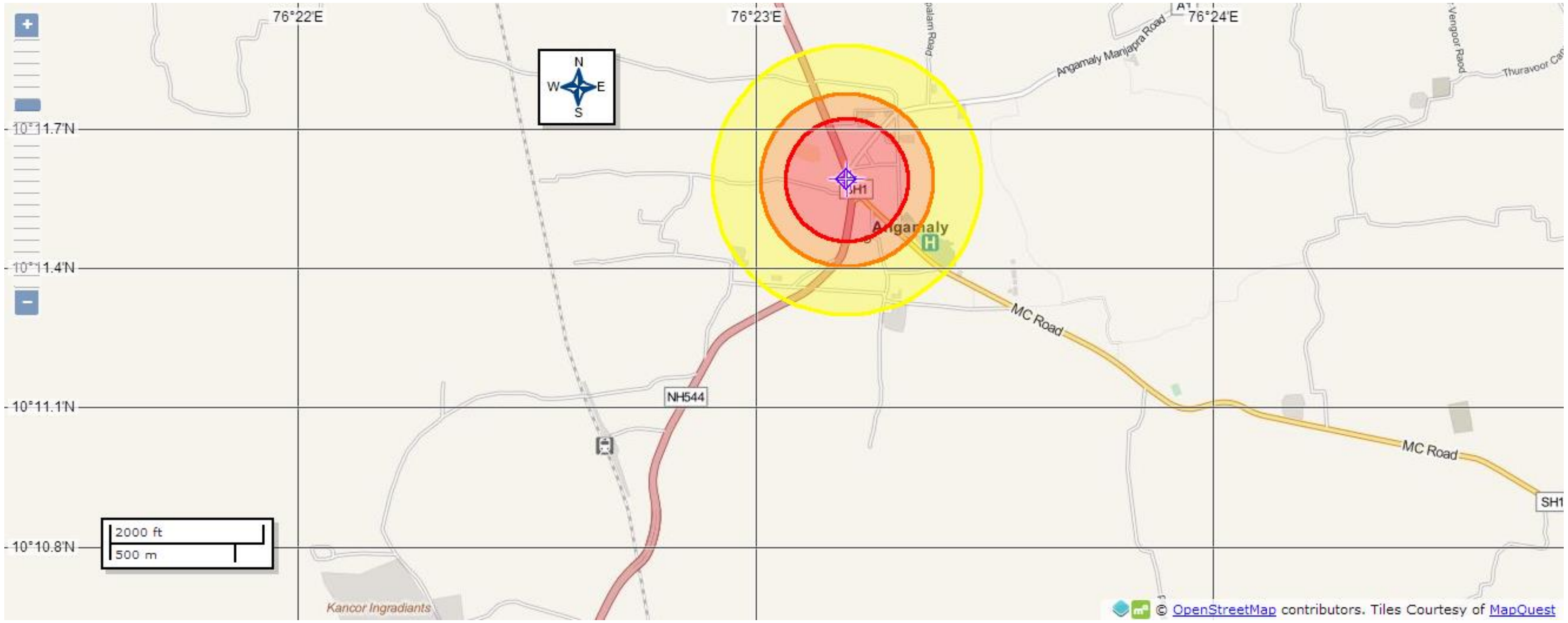

Figure 4.10 LPG BLEVE condition in Angamali

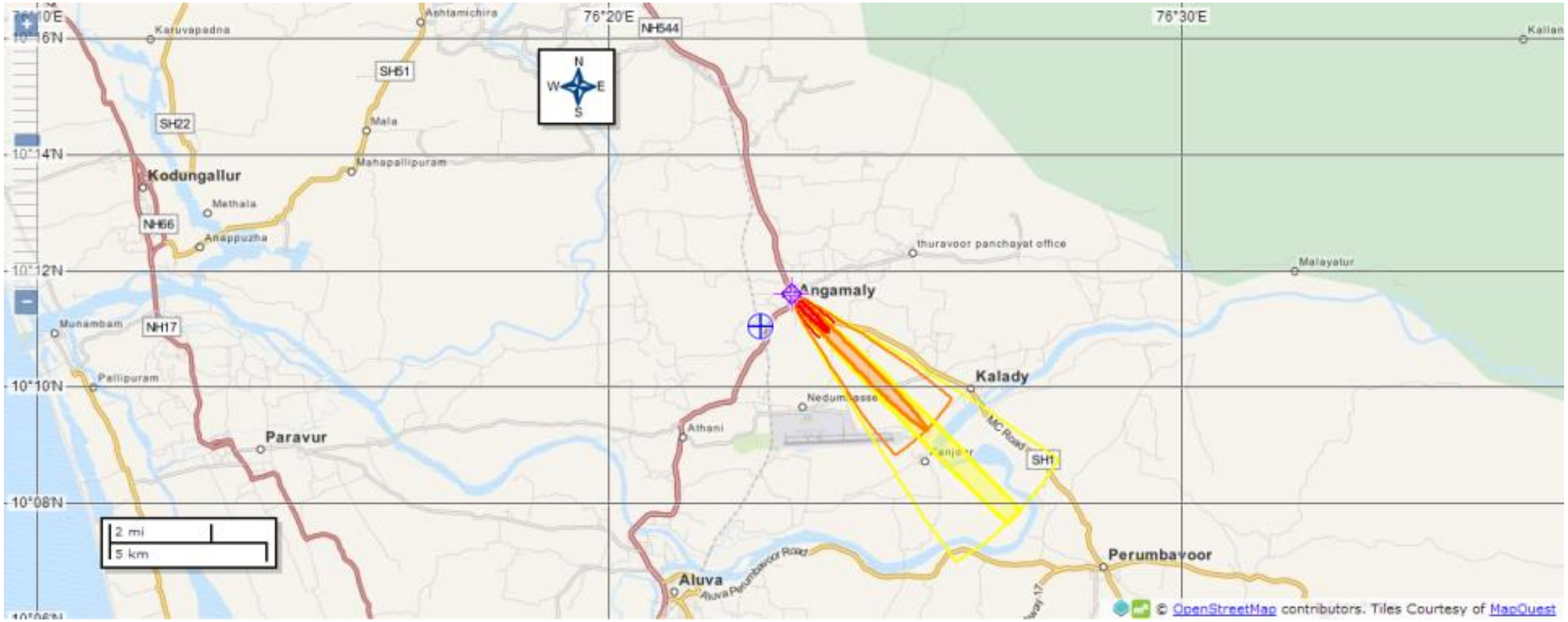

Figure 4.11 Chlorine Dispersion towards the airport- Angamali

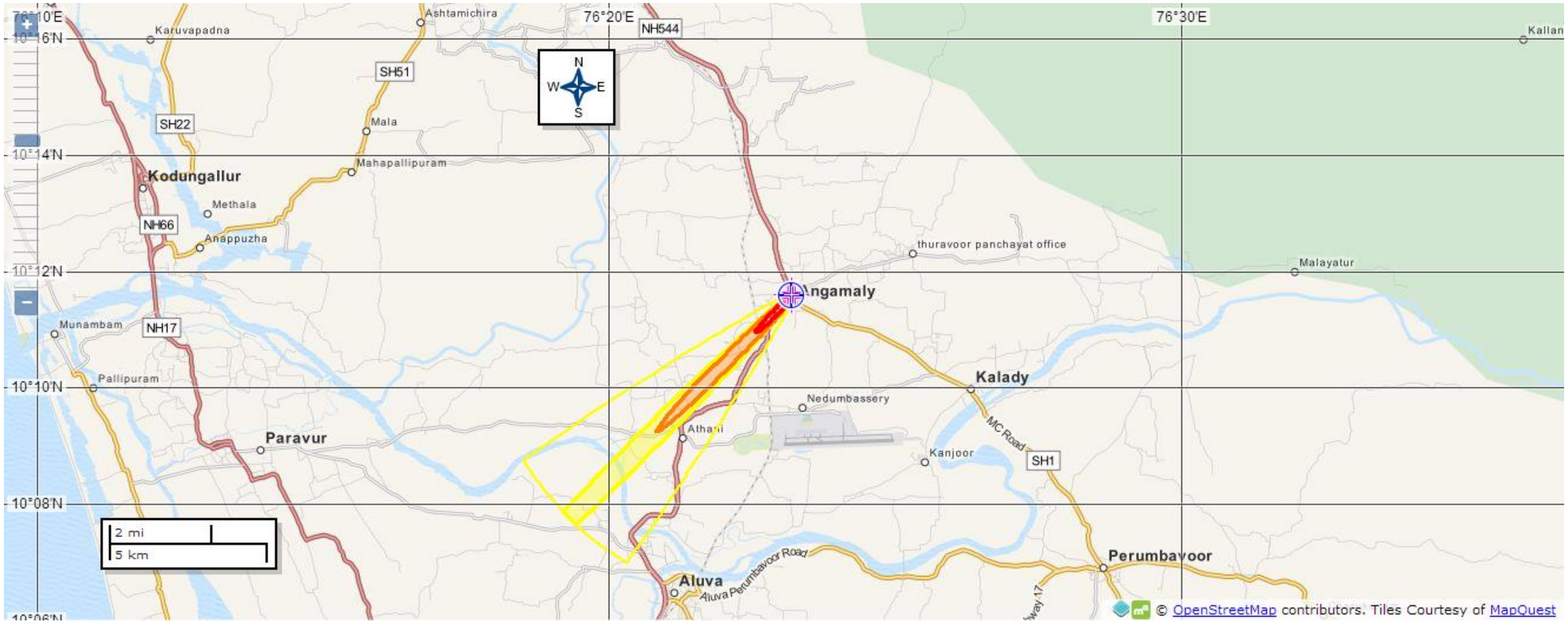

Figure 4.12 Chlorine dispersion along with national highway if wind direction changes

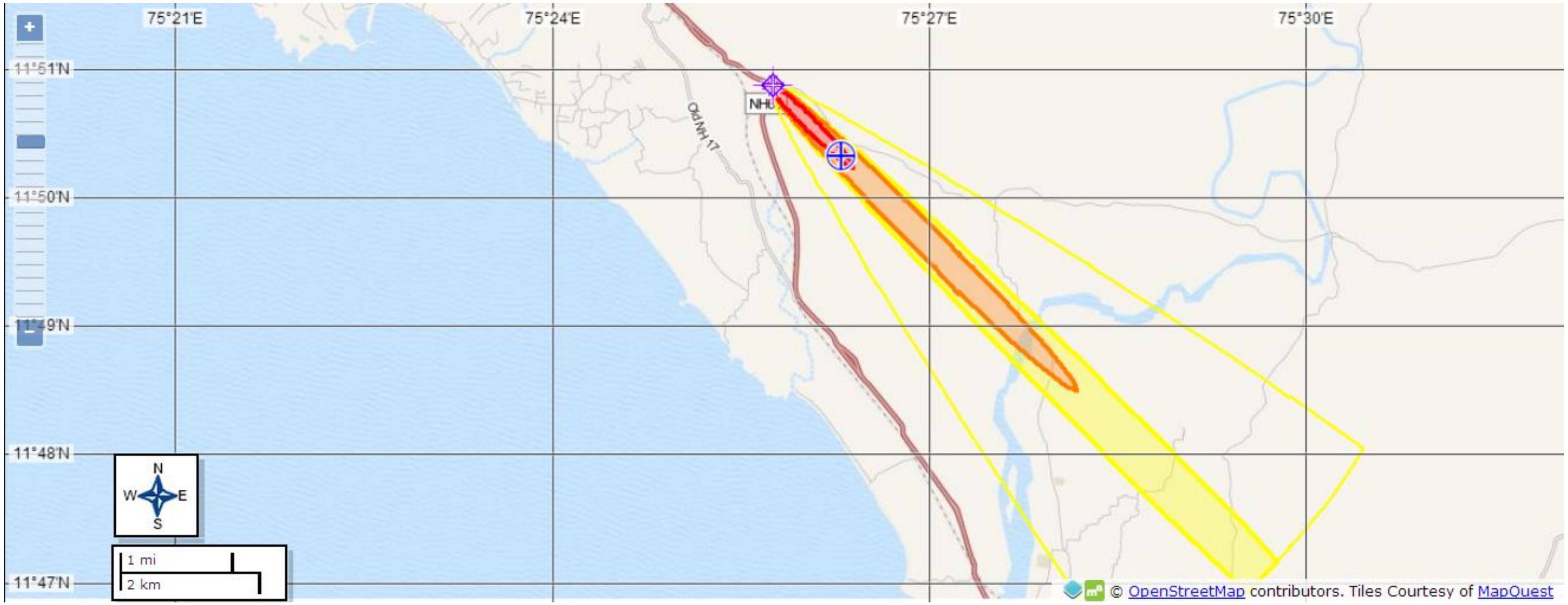

Figure 4.13 Chala, dispersion and threat zone

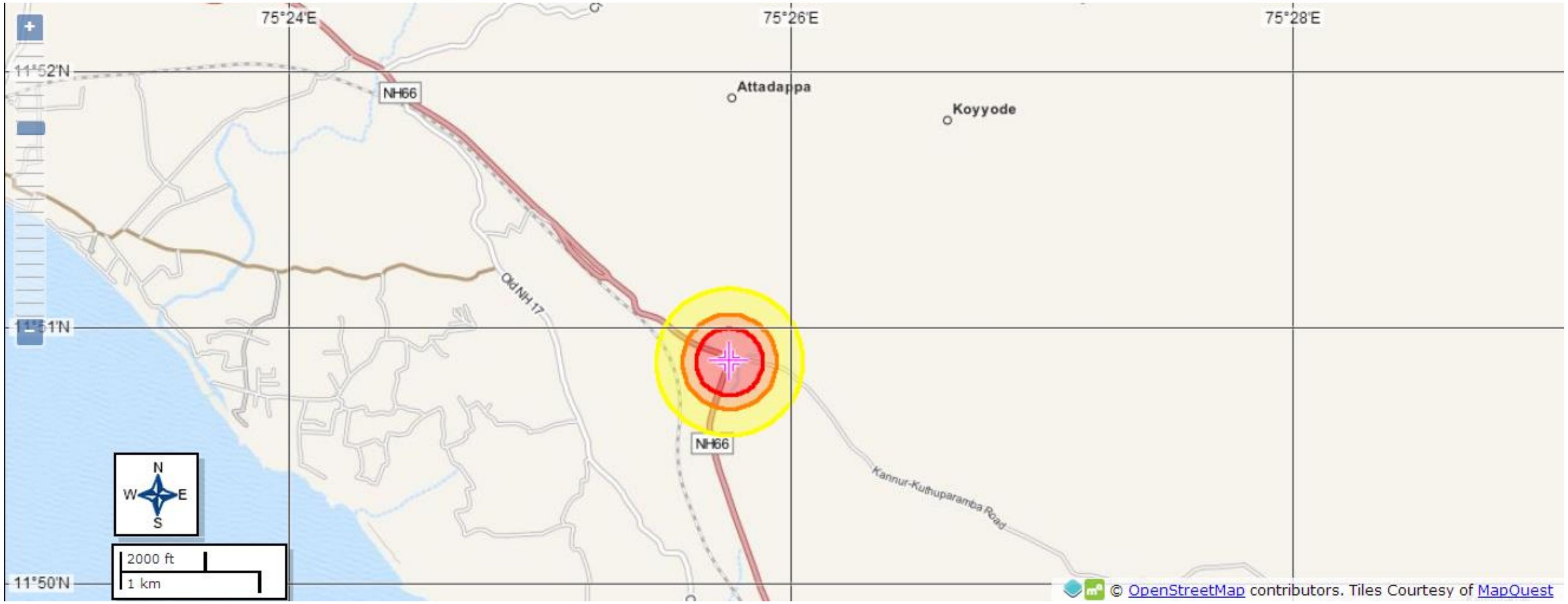

Figure 4.14 BLEVE condition Chala

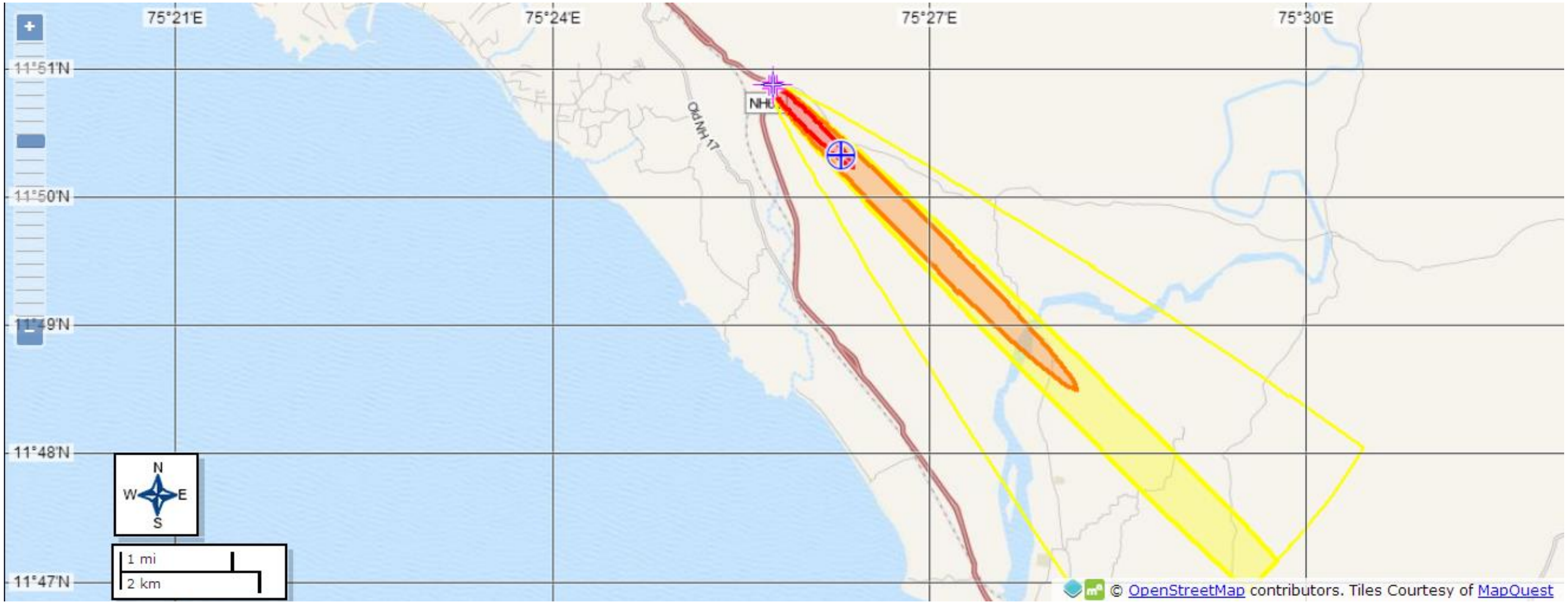

Figure 4.15 Threat Zone Chala

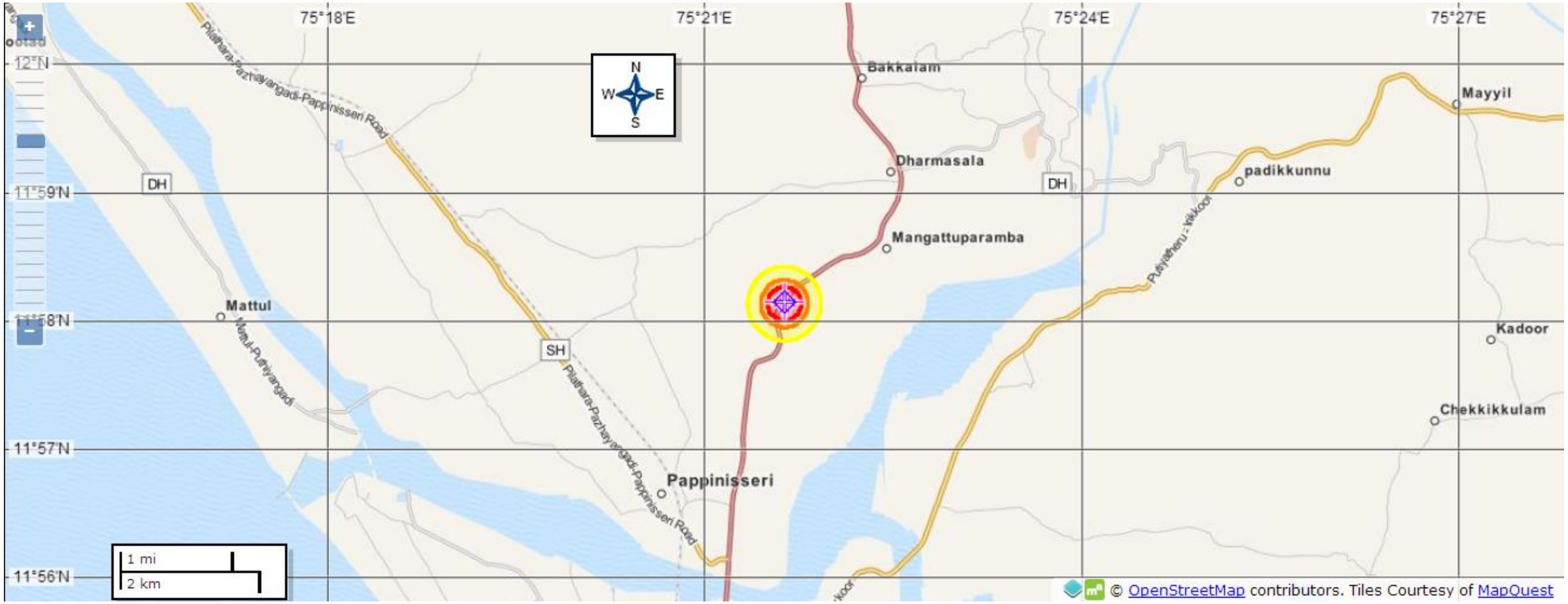

Figure 4.16 BLEVE condition Kalliasseri

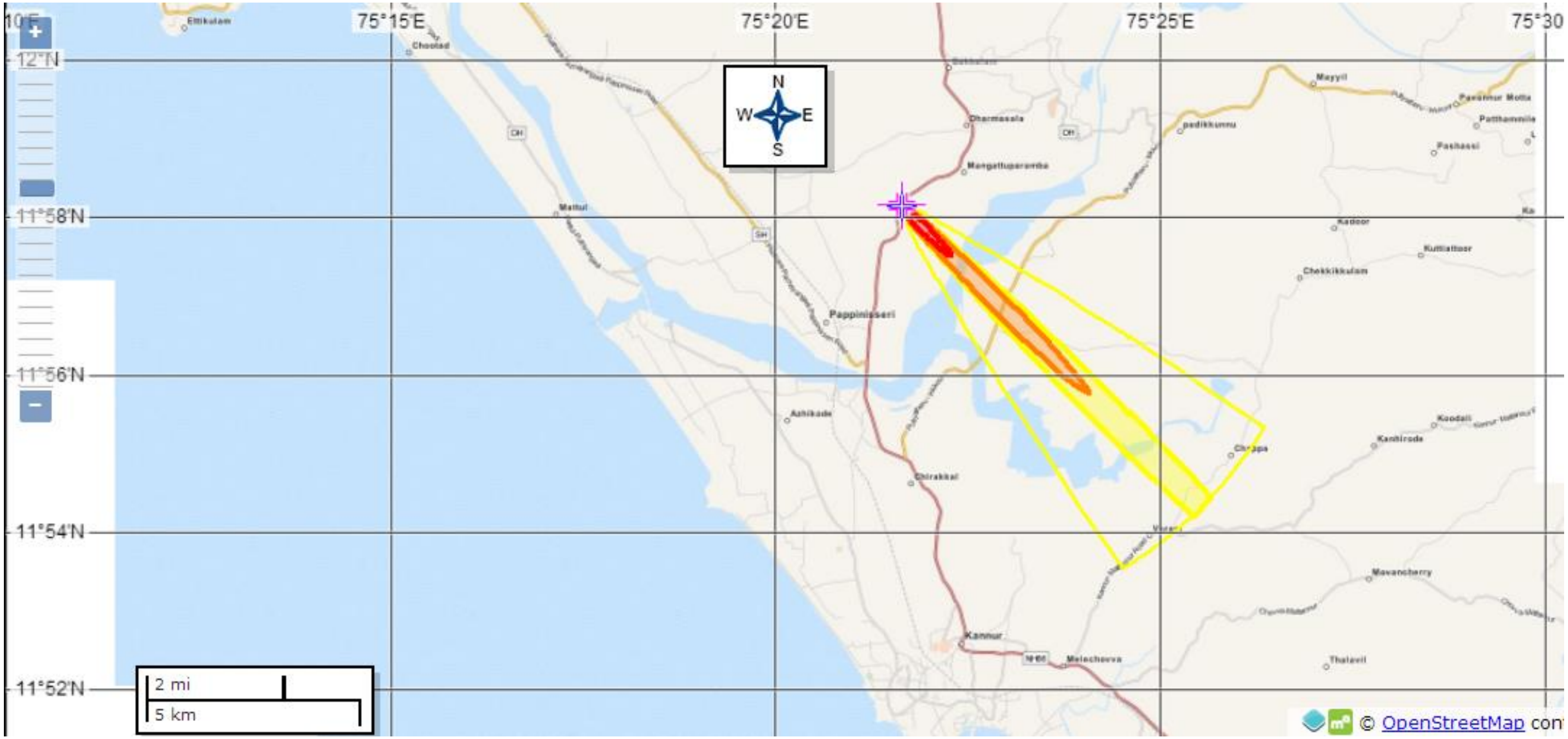

Figure 4.17 Threat Zone Kalliasseri

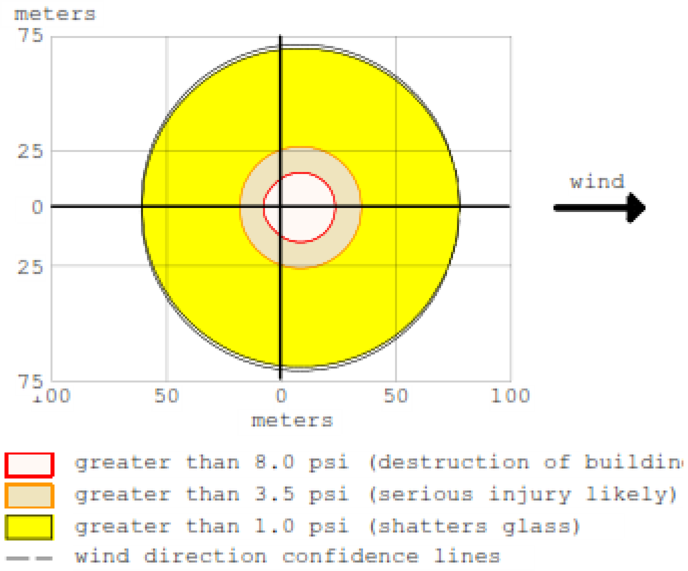

Figure 4.18 Pressure danger zones

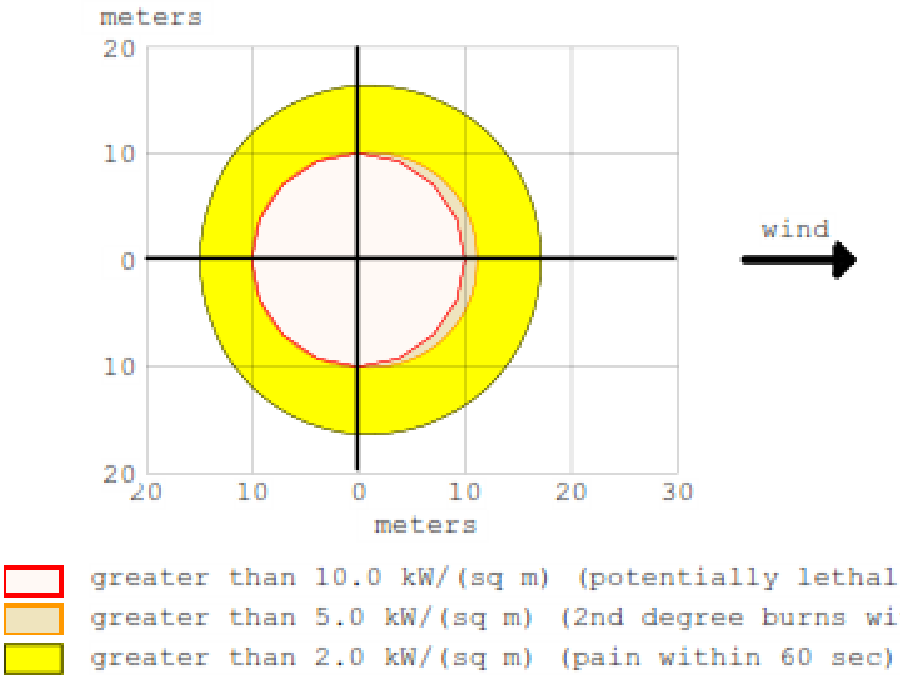

Figure 4.19 Thermal radiation influence zone

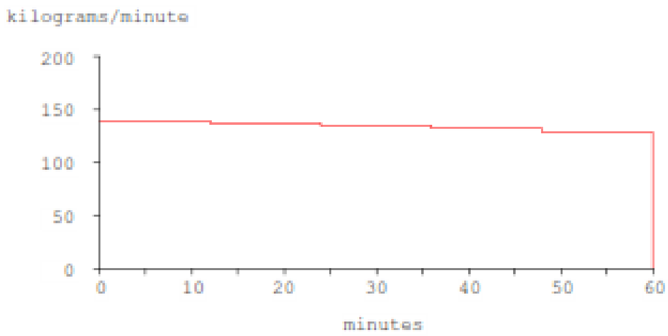

Figure 4.20 Chemical dispersion trend in one minute

4.4 CONSEQUENCE MODELS

Consequence modeling, its effect and risk calculations are evident from the threat zones given in the figures above.

The cases discussed are belonging to the category:

1. Jet Fire due to leakage from holes in the bottom of tanks (cracks in the drain pipes) carrying LPG after overturning the tanks in accident.

2. Pool fire with vapour cloud, again due to the leakage from holes in the bottom of tanks cracks in the drain pipes) carrying LPG after overturning the tanks in accident.

3. Threat Zone without fire, again due to the leakage from holes in the bottom of tanks cracks in the drain pipes) carrying LPG after overturning the tanks in accident.

The detailed calculations are not provided here as we are interested only in the influential zone, based on the developed model. But all the values are at par with thermal radiation from such pool fires as modelled using the point source model given in the spreadsheet in CCPS, Guidelines for Chemical Process Quantitative Risk Assessment (CPQRA)[6].

Since the effects, problems and measures to be taken at different threshold values are given in the Material data sheet, at the first part of the model, it is not reproduced here.

4.4.1 Estimation of risk

The estimation of the risk as per CPQRA, belongs to two category. Individual Risk and Societal Risk.

4.4.2 Individual Risk

CCPS Guidelines for CPQRA [6] defines individual risk as “Individual risk contours show the geographical distribution of individual risk. The contours show the expected frequency of an event capable of causing the specified level of harm a specified location, regardless of whether or not anyone is present at that location to suffer harm. Thus, individual risk contour maps are generated by calculating the individual risk at every geographic location assuming that somebody will be present and the subject to the risk of 100% of the time.”.

Theoretical background of Calculation of Individual risk per annum:

$$\text{IRx}, \mathrm{y} = \sum_{i=1}^{n} IR\ x, y, i \quad \text{-----Eq 5.1}$$

Where

IRx,y = the total individual risk of fatality at a geographical location x, y (chances of fatality per year)

IRx,y,i = the total individual risk of fatality at a geographical location x, y from incident outcome case i (chances of fatality per year)

n= the total number of outcomes cases considered in the analysis

$$IR_{x,y,i} = f\, P_{f,I} \text{ ----Eq 5.2}$$

Where

f = frequency of incident outcome case i, from frequency analysis (per year)

Pf,i = Probability that an incident outcome case i, will result in a fatality at location x,y from consequence and effect models.

As a simplified approach, weather conditions are assumed to be stable in the model while making the plots. Individual risks for thermal radiation and Vapour cloud Explosion were plotted and safe distance marked in the graph as well as in the maps.

4.4.3 Societal risk

Societal risk is the risk to a group of people. It is expressed in terms of frequency distribution of multiple casualty events (F-N curve). For the collected data F-N curve was plotted as in Fig. 4.21.

4.5 ACCIDENT CAUSATION MODEL

The accident cases during HazMat transportation in the state of Kerala is indicated in Table 4.2. Overall fatal cases are shown in one column, while the accidents occurred in various road geometries are shown in next three columns. Over speeding cases are indicated in the next column. Overturning cases are in the last column. When we compare the overturning cases and fatal cases it is evident that all overturning cases are not fatal.

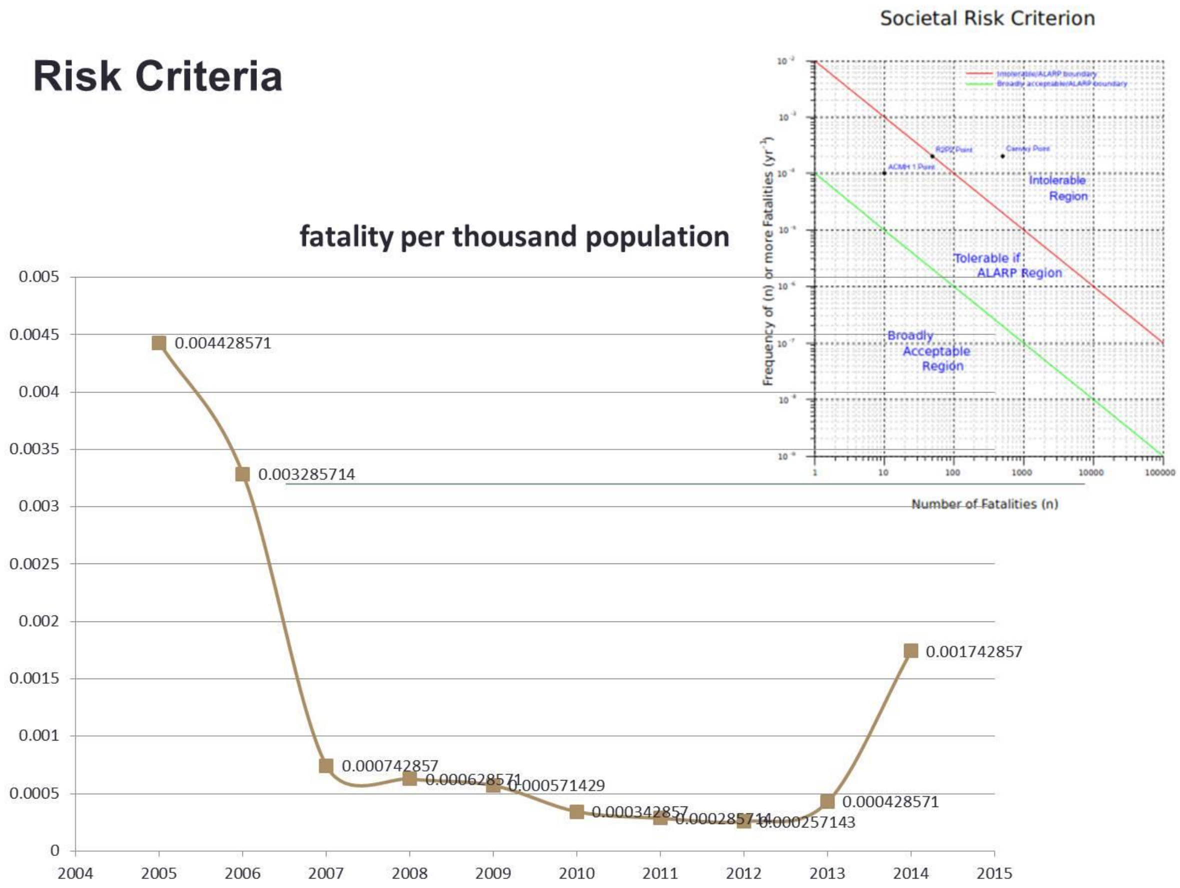

Figure 4.21 F-N curve

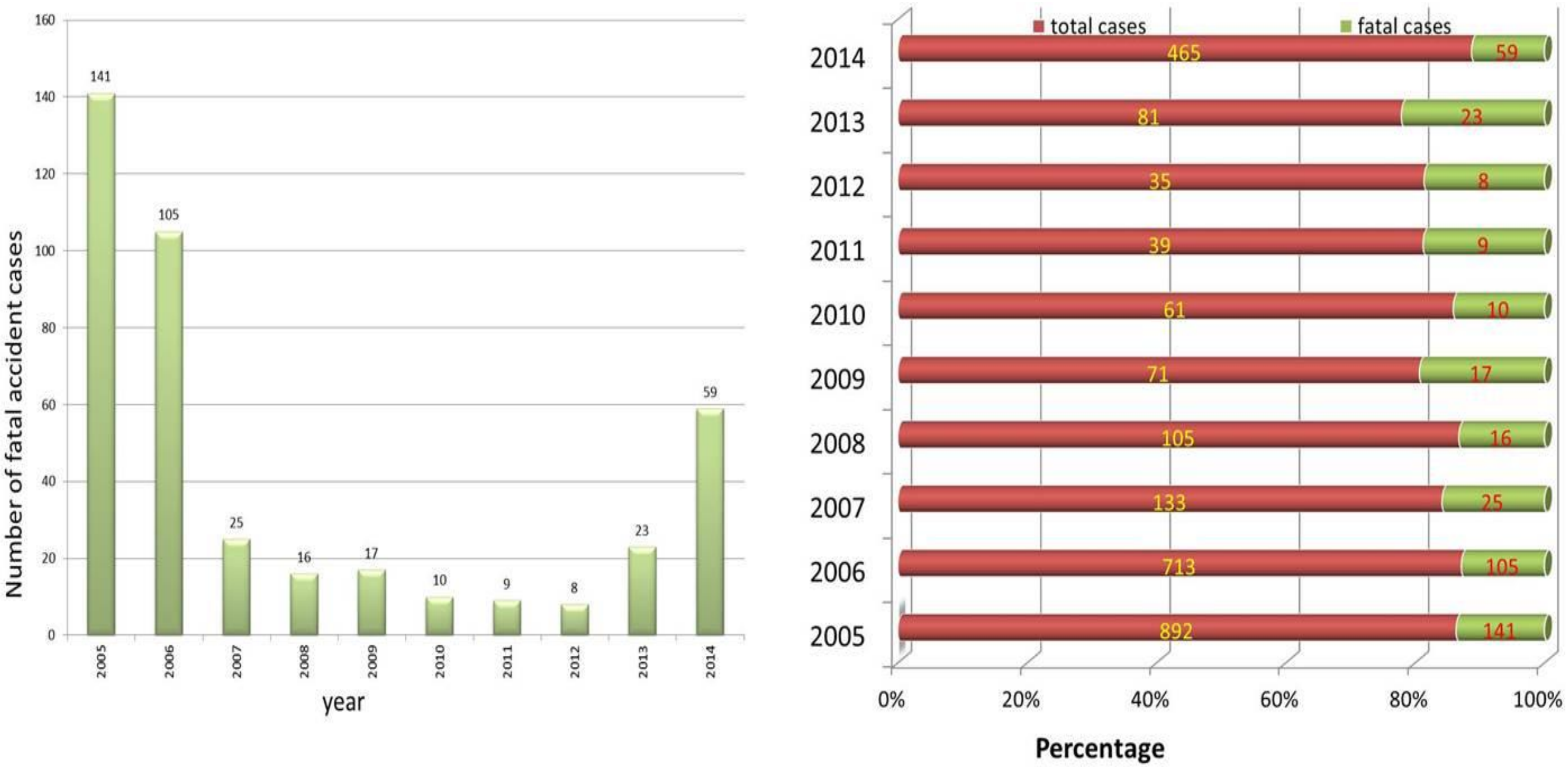

Figure 4.22 Fatal cases of accidents

TABLE 4.2 ACCIDENT DATA WITH ROAD GEOMETRY AND OVERTURN CASES						
Year	**Fatal**	**Junction**	**straight geometry**	**curved**	**over speed**	**over turn**
2010	10	127	62	74	112	12
2011	9	148	68	82	103	14
2012	8	144	74	97	108	15
2013	23	152	83	110	118	16
2014	59	186	99	114	130	18
Total	109	757	386	477	571	75

The number of overturning cases in which the toxic release was happened through a tank opening (drain pipe crack and subsequent release of chemical) against the last known speed of the vehicle is provided in Table 4.3.

TABLE 4.3 ACCIDENT DATA WITH SPEED RANGE DURING OVERTURNING AND TANK HOLE SIZE		
Speed range (kmph)	**Overturning cases (number)**	**Average Hole size (mm)**
30-35	5	6
36-40	5	7
41-45	7	9
46-50	7	12
51-55	7	15
56-60	10	18
61-65	14	20
66-70	8	22
71-75	15	25

Even though direct correlation is not there with the speed and hole size, it can be used as an indicator in the calculation of affected area or affected distance in case of a toxic release as BLEVE or Jet fire as given in Fig. 4.6 and Fig. 4.7 provided in the analysis of Chala LPG release analysis as in Case 2. This is represented in Fig. 4. 23.

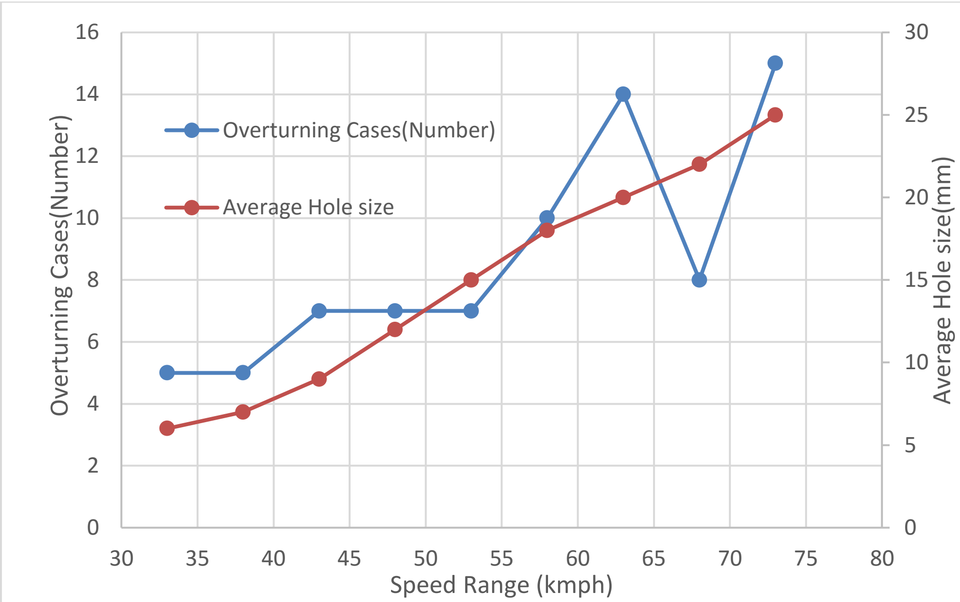

Figure 4.23 Speed range and average hole size against overturning cases

Based on the data given in Table 4.3, if we plot the last known speed of the vehicle before overturning and the maximum size of the hole developed in the tank, different correlations are possible.

The logarithmic plot (Fig. 4.23a) gives the trend line equation as $y=8.882\ln(x)+2.2549$ where y is the developed hole size in the tank corresponding to a speed in kmph. The R^2 value is 0.8756.

But on analysis, the real values are different from the trend line values in lower speed ranges as well as in the higher speed ranges. So this cannot reflect the real incident scenario.

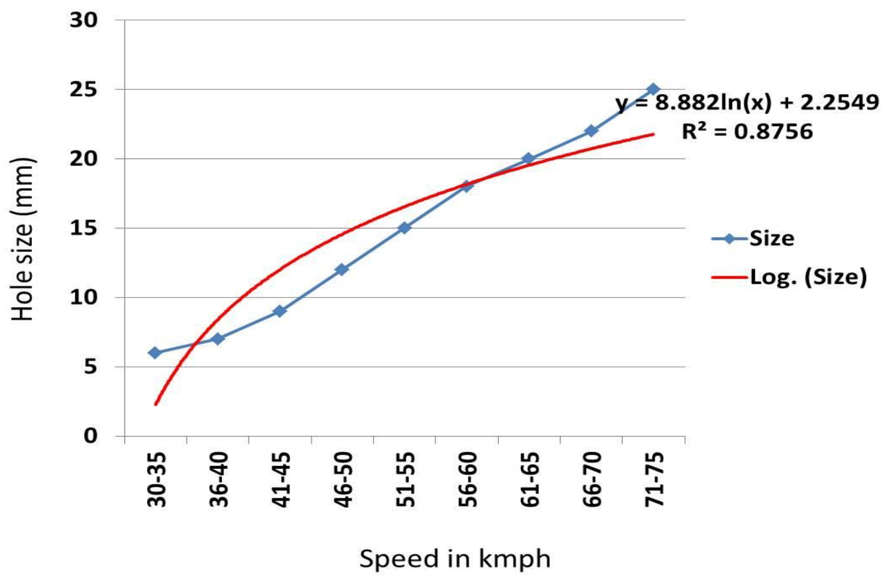

Figure 4.23a Speed vs Hole size (logarithmic fit)

A power plot (Fig. 4.23b) gives the trend line equation as $y=4.931x^{0.7002}$ where y is the developed hole size in the tank corresponding to a speed in kmph. The R^2 value is 0.9515. In this case, in the lower speed ranges as well as in the upper speed ranges, the trend line is slightly deviating from the observed data. So this also will not reflect the real scenario.

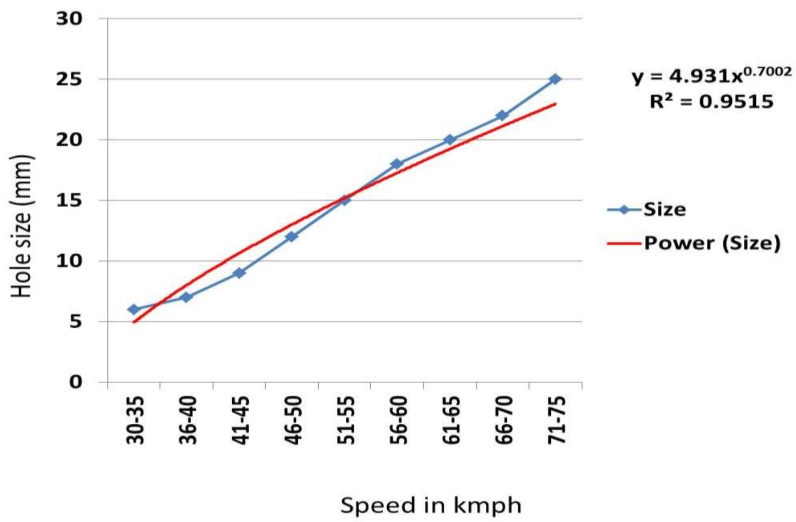

Figure 4.23b Speed vs Hole size (power fit)

An exponential plot (Fig. 4.23c) gives the trend line equation as $y=5.2734e^{0.1858x}$ where y is the developed hole size in the tank corresponding to a speed in kmph. The R^2 value is 0.9709.

On analysis the trend line best suits for the speed ranges up to 45 kmph, but in higher speed ranges the tentative values are either on the upper side or on the lower side than the real values. The number of cases when we considered, only 17 cases out of 78 is falling in this range. In the real sense, 45 kmph is only the permissible speed in the sector and not an over speed, the attribute "over speeding" will not be justified.

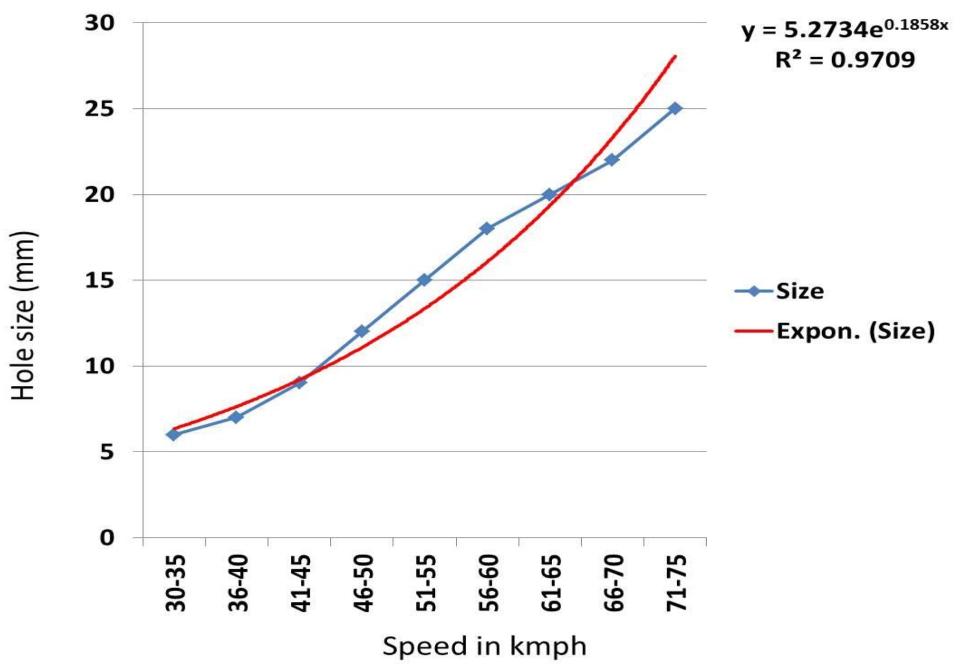

Figure 5.23c Speed vs Hole size (exponential fit)

A linear plot (Fig. 4.23d) gives the trend line equation as $y=2.4833x+2.4722$ where y is the developed hole size in the tank corresponding to a speed in kmph. The R^2 value is 0.9923 which indicates a high degree of correlation. The trend line very well explains the data within the speed range of 55 kmph and above, which is generally an over speed in majority of the road sectors.

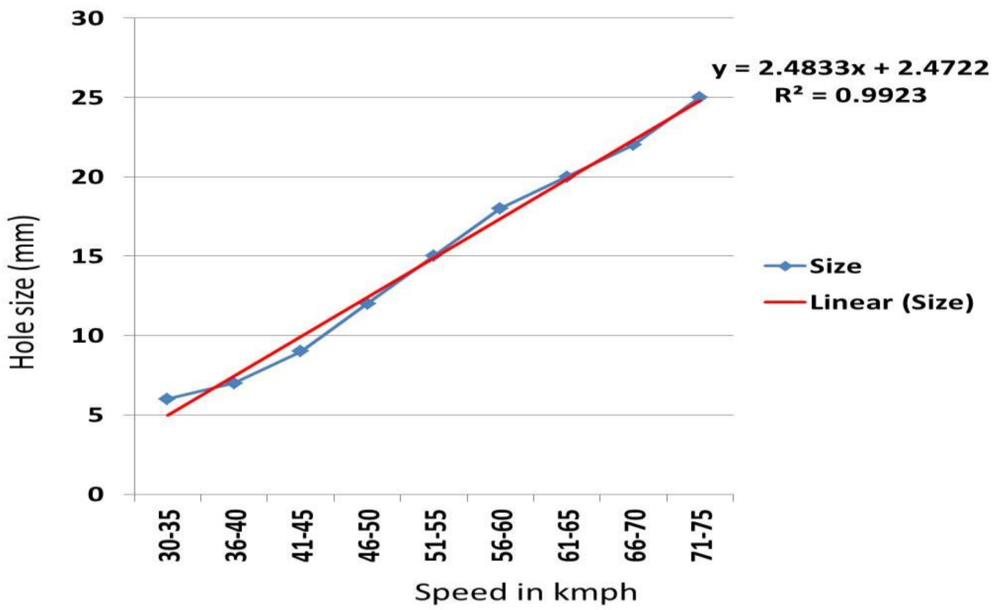

Figure 4.23d Speed vs Hole size (linear fit)

A slight modification of the linear trend with a second degree polynomial plot (Fig. 4.23e) gives the trend line equation as $y=0.0314x^2+2.1695x+3.0476$ where y is the developed hole size in the tank corresponding to a speed in kmph. The R^2 value is 0.9931, which is better than 0.9923. Also it gives better predictions from a speed range of 48 kmph.

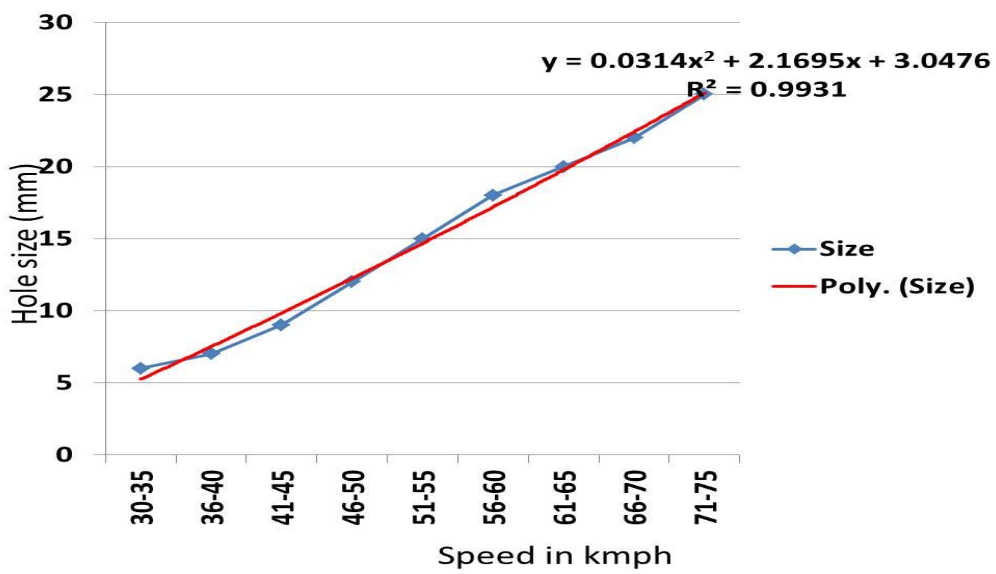

Figure 4.23e Speed vs Hole size (polynomial fit)

In the broader context, correlation will not reflect all causative factors and all correlations may be causative in nature. But here, when comparing the real scenario, the over speeding and thereby overturning of the vehicle is the causative factor. It is becoming highly risky because of the toxic release through the holes developed in the tank, because of the effect of overturning.

In Summary, a three dimensional dynamic problem of movement of a HazMat in the bullet tanker can be analysed in the accident scenario, with known limited parameters. Once the HazMat transport vehicle is over speeding and because of that if it gets overturning, the entire moving tank is coming to standstill and all the variables of speed is getting eliminated. This redundancy in speed will make the accident condition as simple as a tank source is leaking with certain known parameters, which can be analysed with ALOHA either under BLEVE or jet fire as the case may be. The results obtained in this analysis are more or less same as that of the accident scenario where severe burns and multiple devastations have happened in the threshold zones. So the accident causation model suggested is valid and can be used for similar cases.

4.6 MAIN GAPS OF THE METHOD:

It starts with a real failure scenario, based on the past history. But historical frequencies vary depending on the location, climatic conditions and time of occurrence. In most of the cases, mitigative measures taken and the rescue operations made are explored while the causal mechanism is not explained. More over:

- Assumptions are sometimes not transparent
- If a real scenario is missed the QRA process may not be able to analyze it.
- In this method, effect of mitigation measures cannot be linked with risk reduction.
- Updating a QRA study is time consuming.

4.7 SUMMARY OF LIMITATIONS OF QRA

Generally certain limitations are there in QRA. The researcher's personal experience in conducting QRAs related to transportation highlights following limitations:

i. Uncertainties in data for failure frequencies, lack of precision in models and difficulties in identifying common cause failures. This may vary from model to model and according to different scenario.
ii. Assumptions are not visible to all concerned, only the developer of model can explain.
iii. Models are static, difficulties to incorporate changes or variations and difficult to change
iv. Requires considerable specialist efforts and time
v. Software used are costly, and proprietary, calculations are not transparent.

4.8 CHAPTER SUMMARY

The modeling of the accident situations were done with ALOHA. The societal risk as well as individual risk corresponding to various scenarios calculated. Then various correlations with the last known speed of the vehicle before overturning and the dimension of the hole developed in the tank source (major parameter in the accident) was made. Significance and relevance of these correlations were explained in detail in this chapter.

CHAPTER 5
INTERSECTION ANALYSIS

5.1 GENERAL

From the accident analysis data, it was revealed that the major cause of the accident is overspeeding. This was related to the contribution from Driver and Vehicle in the DVE model. We have analysed this in detail with mitigative measures using ICT devices. Second major cause depicted was road conditions. Majority of the accidents are happening at road intersections. In HazMat transportation also, the causal factor of risks starts at accident scenario. The entry and exit from a road intersection to a vehicle is critical if the flow is very high and the PCU is almost saturated. The condition becomes worse when the conflict points in the intersections are more.

For example, when a vehicle travelling through the left lane wants to turn right means it will be affecting the traffic in two lanes, namely the left as well as right. A temporary stop for the traffic in one line is essential. Either by a signal or by a manual mechanism this stop for the flow has to be assured. Otherwise, a head on collision, a rear end collision, or a side collision can happen. When this collision happens for a TT with HazMat under pressure, any impact is serious. Controlled intersections are a solution for this and where space permits intersections are required to be changed to roundabouts which are designed to achieve maximum Level of Service (LOS).

If SIDRA software proprietary software) is not used, the calculations can be made with HCM Method (which is used for the simulation in SIDRA), analytically getting the same Level of Service and Flow Volumes as outlined in the Tables given in Appendix 1; but calculations are tedious. The detailed manual calculations are not attached here, which is almost at par with the simulations done with SIDRA and provided in Appendix 1.

5.2 INTERSECTION DETAILS

To reduce the number of conflict points and thereby to reduce the accidents, a typical design for an intersection in Kerala conditions is adopted. Here a signalised intersection (Fig. 5.1) is designed first with the known traffic flow and volume data and an alternative to this signalized intersection if space permits, a roundabout, also attempted by replacing the intersection (Fig. 5.2).

The parameters used in the design are provided in the Tables given in Appendix 1.

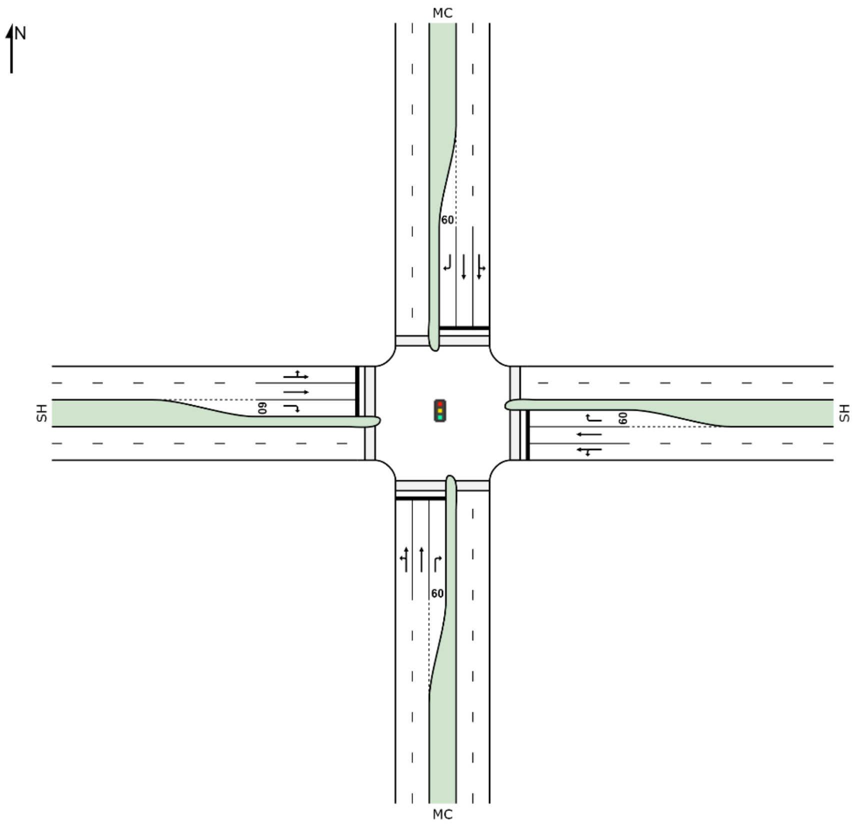

Figure 5.1 Signalised intersection, Fixed time

The design is made for a National Highway with two lanes in one direction crossing a State Highway, permitting all turns.

The parameters used are:

Signals - Fixed Time Cycle

Time = 100 seconds (Practical Cycle Time)

Variable Sequence Analysis applied.

The results are given for the selected output sequence.

Sensitivity Analysis (Critical Gap & Follow-up Headway): Results for Parameter Scale = 80.0 %

Basic Parameters:

Intersection Type: Signalised - Fixed Time

Driving on the left-hand side of the road

Input data specified in Metric units

Model Defaults: Standard Left

Peak Flow Period (for performance): 45 minutes

Unit time (for volumes): 60 minutes.

SIDRA Standard Delay model used

SIDRA Standard Queue model used

Level of Service based on: Delay (Highway Capacity Method 2000)

Queue percentile: 95%.

Movement timing information used for the intersection as a fixed time signal with practical cycle time of 100 second is given in Table A.1. Critical movements and ccycle time is given in Table A.2. Here flow ratio not used for cycle time calculations and the adjusted lost time equals the required movement time. The phase information for the fixed time signal is given in Table A.3, which clearly indicates the start and end of green time in various directions. Variable signal phasing is given in Table A.4 which indicates an average delay of 34.8 second.

As part of the intersection negotiation various travel data is analysed in Table A.5 and Table A.6. Here travel speed, travel time and travel distance is calculated. While calculating the travel time the cruise times, intersection delays including acceleration, deceleration and idling delays are included. Movement speeds and geometric delay is provided in Table A.7. Coordinated information and actuated signal information is provided in Table A.8. Movement capacity parameters are analysed in Table A.9. The Flow Ratio values given in this tables are calculated for signal timing purposes. For movements with two green periods they are subject to balancing as relevant to determining required movement times given in the movement timing information table. Movement performance is given in Table A.10. As part of lane performance and capacity information, lane performance is provided in Table A.11 and lane flow and capacity information is provided in Table A.12. Basic saturation flow in this table is adjusted for lane width, approach grade, parking manoeuvres and number of buses stopping. Coordination parameters and progression factors are given in Table A.13. Lane, approach and intersection performance is analysed in Table A.14 considering the queue values with 95% queue. Driver characteristics (Table A.15), flow rates in various directions (Table A.16) with a unit time for volume as 60 minutes, origin destination flow rates by movement class (Table A.17), flow rates for heavy vehicles (Table A.18), lane flow rates at stop line in vehicles per hour (Table A.19), exit lane flow rates (Table A.20), down stream flow rates for exit roads (Table A.21) and sensitivity analysis (Table A.22) are also provided.

5.3 CONVERSION OF INTERSECTION TO A ROUNDABOUT

When the signalised intersection is converted into a roundabout (Fig. 5.2), basic parameters used for the design are given in Table A.23.

Circulating and exiting stream parameters of the roundabout is provided in Table A.24. Round about gap acceptance parameters (Table A.25) and circulating flow rates (Table A.26), approach lane flow rates (Table A.27) are also analysed.

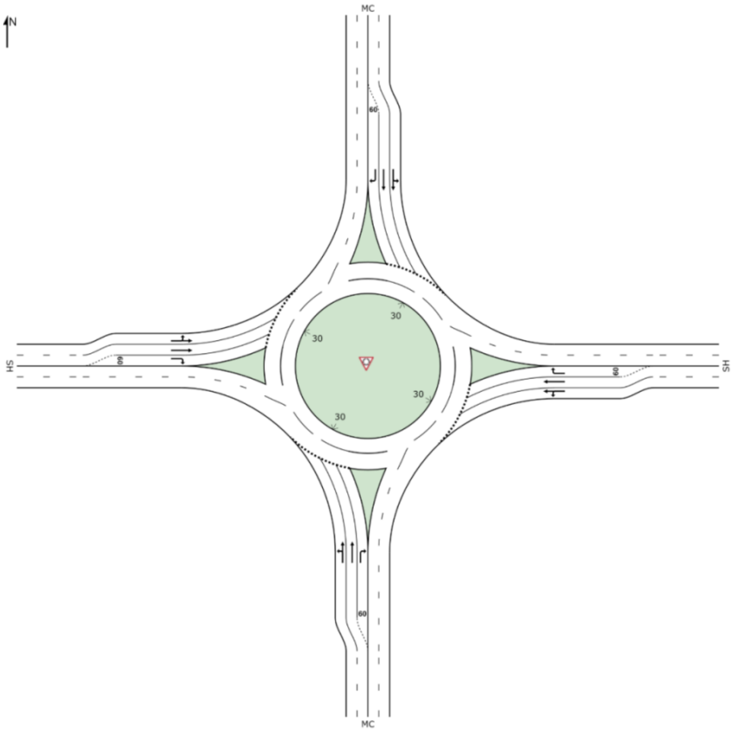

Figure 5.2 Conversion of intersection to Roundabout

Similar to the intersection analysis, travel speed, travel time and travel distance is provided in Table A.28, which indicates a running speed i.e. average speed excluding delays as 55.5 kmph, which is considerably good. The other details like intersection negotiation data (Table A.29), movement speeds and geometric delay (Table A.30), movement capacity parameters (Table A.31), movement performance (Table A.32), lane performance (Table A.33), lane flow and capacity information (Table A.34), lane, approach and intersection performance (Table A.35), Driver characteristics (Table A.36), total flow rates in all movement classes (Table A.37), flow rates for light vehicles (Table A.38), flow rates for heavy vehicles (Table A.39) and sensitivity analysis (Table A.40) indicate considerable improvement in comparison with the intersection analysis results.

Based on the above results it is easy to understand that any modification made on the traditional road geometry may improve the driver characteristics and thereby it can be a causal factor in reducing the accidents.

Many researchers already discussed this in detail. As in the case of ICT devices being a causal factor in reducing the number of road accidents, smoothening of the traditional bottlenecks in traffic may enhance the safety related to traffic. The number of conflict points are reduced considerably in the roundabout design, possible collisions are also will be reduced. One serious problem that may arise, and has to be analysed in detail in further studies is the probability of accidents because of the increased speeds in movements in the roundabouts in comparison with the intersections.

5.4 CHAPTER SUMMARY

A typical road intersection design was attempted in this chapter based on the outcomes of the accident causation model. Then the parameters while re-designing of the intersection into a roundabout is explored. The comparison is done between the simulated results and Level of Service is assessed. Detailed results are provided in Appendix 1.

CHAPTER 6
CONCLUSION

6.1 RESEARCH OUTCOMES

This research has the following main outcomes:

i. Comprehensive list of the causes and effects of various road accidents were made. This was correlated to the Driver, Vehicle and Environment parameters to develop the causation model.
ii. Credible road accident scenarios during HazMat transportation were modeled. Hazards, threats and influential areas identified.
iii. Societal Risks was examined based on the tolerability of risks by constructing F-N diagrams.
iv. Projected consequences at a distance of 1 km was calculated and compared with the QRA.
v. Detailed analysis of the intersections based on the causation model was done with latest transportation parameters (flow, volume, lane conditions etc. for signalised intersections and non signalsied intersections. Accident causation model for various risk criteria developed and discussed.

6.2 CONCLUSION

The accident causation model for general transport system is available in various countries according to the climatic conditions and territorial characteristics. But accident causation model with specific reference to the HazMat is not available in Kerala or India. The intersection analysis incorporating the transportation risks of HazMat is seldom available. In this prospect, the outcome of this research can be extensively used for re-planning the intersections, modifying the road contours with varying topographies, channelizing or segmenting the traffic at potential hot spots. Moreover, the traffic analysis with single lane conditions, multilane conditions, two directional flow conditions, etc. also can be made specific with the associated risks. Various control measures also can be planned based on the analysis. The causation model prioritise the root causes of an accident, which will be useful to control/manage the present transport risks and to refine future TRA studies. Also it will be useful to identify and to establish points of strategic importance in the emergency responses based on IVMS input.

6.3 FUTURE WORK

i. The development of an Accident Causation Model that can be customized to individual or company needs, with specific route and chemical data incorporated in it.

ii. Incorporation of Experts' opinion in refining the developed model.

iii. Methodology for incorporation of more environmental factors, including the complex reactions of HazMat with the environmental elements.

iv. In this research, a single element, overspeeding is identified as the root cause of the accidents during the HazMat transportation in the selected stretches. The severity is because of the continuous actions like overspeeding and then overturning, holes developed in the tanks because of overturning, then it starts leaking, and further consequences due to the leaking. Other factors involved in this sequence also to be explored in further studies.

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APPENDIX 1

INTERSECTION DESIGN DETAILS

The details of the intersection analysis as discussed in Chapter 5 are provided here. First the attempt is to design an intersection with the existing traffic data. The negotiated design of the intersection is provided in figure A.1 below.

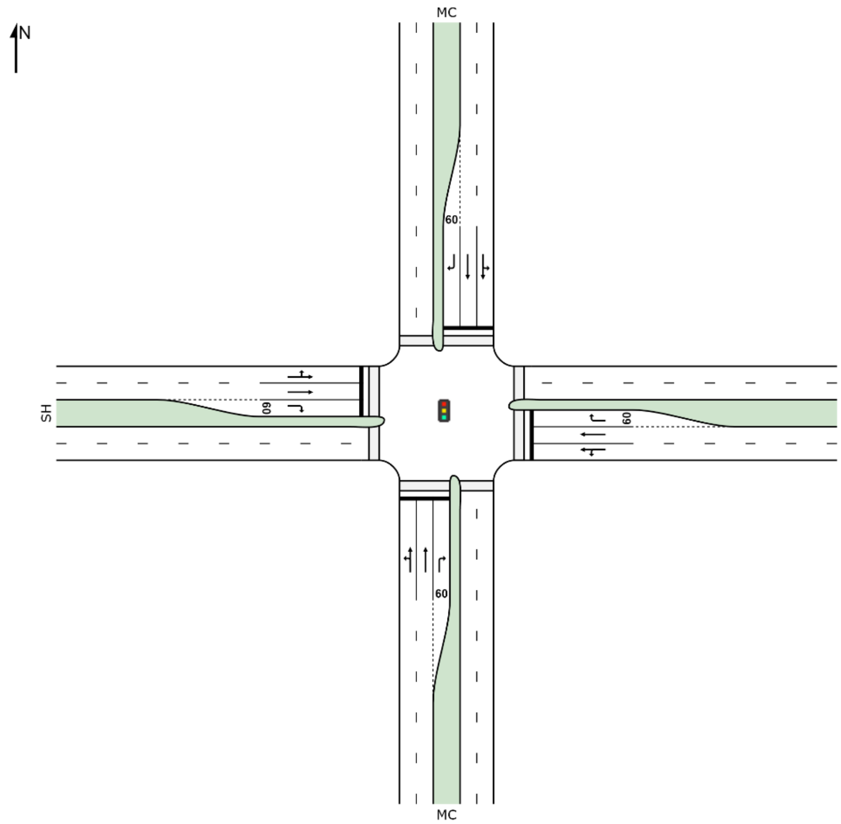

Figure A.1 Signalised intersection, Fixed time

Parameters used are:

Signals - Fixed Time Cycle

Time = 100 seconds (Practical Cycle Time)

Variable Sequence Analysis applied.

The results are given for the selected output sequence.

Sensitivity Analysis (Critical Gap & Follow-up Headway): Results for Parameter Scale = 80.0 %

Basic Parameters:

Intersection Type: Signalised - Fixed Time

Driving on the left-hand side of the road

Input data specified in Metric units

Model Defaults: Standard Left

Peak Flow Period (for performance): 45 minutes

Unit time (for volumes): 60 minutes.

SIDRA Standard Delay model used

SIDRA Standard Queue model used

Level of Service based on: Delay (HCM 2000)

Queue percentile: 95%

Table A.1 movement timing information

Intersection ID: 1 Fixed-Time Signals   Cycle Time = 100 sec (Practical Cycle Time)

Mov ID	Mov Cl.	Mov Typ	PHASE MATRIX First Green Fr	To	Op	Pr	Und	Second Green Fr	To	Op	Pr	Und	Lost Tim 1st Grn	Lost Tim 2nd Grn	Req.Mov.Time 1st Grn	Req.Mov.Time 2nd Grn	Eff. Grn 1st Grn	Eff. Grn 2nd Grn
South: MC																		
1	#		F	A									6		27.0 Min		21	
2	#		F	A									6		27.0 Min		21	
3	#		D	F									6		12.0 Min		6	
East: SH																		
4	#		C	D									6		27.0 Min		31	
5	#		A	B1				C	D				6	6	12.0 Min	27.0 Min	6	31
6	#		*A	B1									6		12.0 Min		6	
North: MC																		
7	#		F	A									6		27.0 Min		21	
8	#		F	A									6		27.0 Min		21	
9	#		*D	F									6		12.0 Min		6	
West: SH																		
10	#		B1	D									6		39.0 Min		43	
11	#		B1	D									6		39.0 Min		43	
12	#		*B1	C									6		12.0 Min		6	
Pedestrian Movements																		
P1		(Ped)	*C	D									21		27.0 Min		16	
P2		(Ped)	*F	A									21		27.0 Min		6	
P3		(Ped)	B1	D									21		39.0 Min		28	
P4		(Ped)	F	A									21		27.0 Min		6	

Current Phase Sequence: Variable Phasing Input Phase Sequence: A B1* B2* C D E1* E2* F (* Variable Phase)
Output Phase Sequence: A B1 C D F

Combined timing results are shown for all Movement Classes except any listed separately.
* Critical Movement/Green Period
H (under heading 'Pr') - "High" priority for green splits specified for all coordinated movements
Movement Types:
Slp: Slip/Bypass Lane Movement; Ped: Pedestrian; Dum: Dummy

Table A2. Critical movements and cycle time

Crit Mov ID	App. and Dest	Green Period	Phases Fr	Phases To	Adjusted Lost Time	Adjusted Flow Ratio	Required Grn Time Ratio	Required Movement Time
6LV	E_N		A	B1	12	-	-	12.0Min
12LV	W_S		B1	C	12	-	-	12.0Min
P1	S_Ped		C	D	27	-	-	27.0Min
9LV	N_W		D	F	12	-	-	12.0Min
P2	E_Ped		F	A	27	-	-	27.0Min
				Total:	90	0.000	0.000	90.0

- Flow ratio not used for cycle time calculations and the adjusted lost time equals the required movement time (=Min or Max as shown in Movement Timing Information)

Cycle Time:	Minimum	Maximum	Practical	Chosen
	90	150	90	100

Table A.3 Phase information:

Intersection ID: 1
Fixed-Time Signals   Cycle Time = 100 sec (Practical Cycle Time)

Phase	Ref. Phase	Change Time	Starting Intgrn	Green Start	Displayed Green	Green End	Terminating Intgrn	Phase Time	Phase Split
A	Yes	0	6	6	6	12	6	12	12%
B1	No	12	6	18	6	24	6	12	12%
C	No	24	6	30	31	61	6	37	37%
D	No	61	6	67	6	73	6	12	12%
F	No	73	6	79	21	100	6	27	27%

Current Phase Sequence: Variable Phasing
Input Phase Sequence: A B1* B2* C D E1* E2* F (* Variable Phase)
Output Phase Sequence: A B1 C D F

Table A 4. Variable signal phasing

```
Intersection ID: 1
 Fixed-Time Signals   Cycle Time = 100 sec (Practical Cycle Time)

 -------------------------------------------------------------------------------------------
       Cycle   Intersn   Eff.   Prac.   Aver.   Stop   Longest   Perf.   Cost
       Time    Deg. of   Int.   Spare   Delay   Rate    Queue    Index   Total
       (sec)    Satn     Cap.    Cap.   (sec)            (veh)           $/h
 -------------------------------------------------------------------------------------------
  Analysed Sequence : A B1 C D F
 *Resulting Sequence: A B1 C D F
         91     0.011    1143  8046.5    34.8   0.54      0.1      0.9   318.5
 -------------------------------------------------------------------------------------------
  Analysed Sequence : A B1 C D E1 F
  Resulting Sequence: A B1 C D F
         91     0.011    1143  8046.5    34.8   0.54      0.1      0.9   318.5
 -------------------------------------------------------------------------------------------
  Analysed Sequence : A B1 C D E2 F
  Resulting Sequence: A B1 C D F
         91     0.011    1143  8046.5    34.8   0.54      0.1      0.9   318.5
 -------------------------------------------------------------------------------------------
   The following phase sequences were not assessed since movements did not run in any phase
     (movements were included in variable phases only):

    A C D F
    A B2 C D F
    A C D E1 F
    A C D E2 F
    A B2 C D E1 F
    A B2 C D E2 F
```

INTERSECTION NEGOTIATION and TRAVEL DATA

Intersection ID: 1
Fixed-Time Signals   Cycle Time = 100 sec (Practical Cycle Time)

Table A.5 travel speed, travel distance and travel time

From Approach	To Exit	Turn	Running Speed km/h	Travel Speed km/h	Travel Distance m	Travel Time s	Total Travel Distance Dem Flows veh-km/h	Total Travel Distance Arv Flows veh-km/h	Tot.Trav. Time veh-h/h
South: MC									
	West	L2	51.2	36.6	1017.5#	100.1#	1.1	1.1	0.0
	North	T1	55.0	38.4	1018.4#	95.4#	1.1	1.1	0.0
	East	R2	50.1	30.9	1018.3#	118.5#	1.1	1.1	0.0
East: SH									
	South	L2	50.7	38.8	1015.7#	94.3#	1.1	1.1	0.0
	West	T1	57.1	49.5	1019.8#	74.2#	1.1	1.1	0.0
	North	R2	50.1	30.9	1018.3#	118.5#	1.1	1.1	0.0
North: MC									
	East	L2	50.4	35.7	1015.7#	102.5#	1.1	1.1	0.0
	South	T1	56.4	38.9	1019.8#	94.3#	1.1	1.1	0.0
	West	R2	49.4	30.6	1018.3#	119.9#	1.1	1.1	0.0
West: SH									
	North	L2	50.3	41.8	1015.7#	87.4#	1.1	1.1	0.0
	East	T1	57.3	47.0	1019.8#	78.1#	1.1	1.1	0.0
	South	R2	49.4	30.6	1018.3#	119.9#	1.1	1.1	0.0
ALL VEHICLES:			52.3	36.6	1018.0#	100.3#	12.9	12.9	0.4

"Running Speed" is the average speed excluding stopped periods.

Travel Time values include cruise times and intersection delays including acceleration, deceleration and idling delays.

Travel Distance and Travel Time values include travel on the External Exit section based on the program-determined Exit Distance or user-specified Downstream Distance as applicable.

Table A.6 intersection negotiation data

From Approach	To Exit	Turn	Negn Radius m	Negn Speed km/h	Negn Dist. m	Appr. Dist. m	Exit Dist. m	Downstr. Dist. m
South: MC								
	West	L2	10.0	20.2	15.7	500	500	NA
	North	T1	S	60.0	19.8	500	500	NA
	East	R2	11.7	21.4	18.3	500	500	NA
East: SH								
	South	L2	10.0	20.2	15.7	500	500	NA
	West	T1	S	60.0	19.8	500	500	NA
	North	R2	11.7	21.4	18.3	500	500	NA
North: MC								
	East	L2	10.0	20.2	15.7	500	500	NA
	South	T1	S	60.0	19.8	500	500	NA
	West	R2	11.7	21.4	18.3	500	500	NA
West: SH								
	North	L2	10.0	20.2	15.7	500	500	NA
	East	T1	S	60.0	19.8	500	500	NA
	South	R2	11.7	21.4	18.3	500	500	NA

Table A.7 Movement speeds and geometric delay

Mov ID	Turn	App. Speeds Cruise km/h	App. Speeds Negn km/h	Exit Speeds Negn km/h	Exit Speeds Cruise km/h	Queue Move-up Sp 1st Grn km/h	Queue Move-up Sp 2nd Grn km/h	Geom Delay sec
South: MC								
1	L2	60.0	20.2	20.2	60.0	29.6		6.0
2	T1	60.0	60.0	60.0	60.0	31.8		0.0
3	R2	60.0	21.4	21.4	60.0	18.3		5.8
East: SH								
4	L2	60.0	20.2	20.2	60.0	20.2		5.8
5	T1	60.0	60.0	60.0	60.0	18.8	42.8	0.0
6	R2	60.0	21.4	21.4	60.0	18.3		5.8
North: MC								
7	L2	60.0	20.2	20.2	60.0	20.2		5.8
8	T1	60.0	60.0	60.0	60.0	35.3		0.0
9	R2	60.0	21.4	21.4	60.0	18.5		6.0
West: SH								
10	L2	60.0	20.2	20.2	60.0	20.2		6.0
11	T1	60.0	60.0	60.0	60.0	45.0		0.0
12	R2	60.0	21.4	21.4	60.0	18.5		6.0

Table A . 8 Coordination and actuated signal information

Intersection ID: 1 Fixed-Time Signals Cycle Time = 100 sec (Practical Cycle Time)

COORDINATION INFORMATION

Mov ID	Turn	Mov Cl.	Control	Stopl Dist. m	Stopl Trav. Time	Coordination	Arv Type	% Arv During Green	Eff. Grn 1st Grn	Eff. Grn 2nd Grn	Green Time Ratio	Pla-toon Ratio
South: MC												
1	L2	LV	FT	NA	NA	Prog (Isolated)	3	21.0	21		0.210	1.000
1	L2	HV	FT	NA	NA	Prog (Isolated)	3	21.0	21		0.210	1.000
2	T1	LV	FT	NA	NA	Prog (Isolated)	3	21.0	21		0.210	1.000
2	T1	HV	FT	NA	NA	Prog (Isolated)	3	21.0	21		0.210	1.000
3	R2	LV	FT	NA	NA	Prog (Isolated)	3	6.0	6		0.060	1.000
3	R2	HV	FT	NA	NA	Prog (Isolated)	3	6.0	6		0.060	1.000
East: SH												
4	L2	LV	FT	NA	NA	Prog (Isolated)	3	31.0	31		0.310	1.000
4	L2	HV	FT	NA	NA	Prog (Isolated)	3	31.0	31		0.310	1.000
5	T1	LV	FT	NA	NA	Prog (Isolated)	3	37.0	6	31	0.370	1.000
5	T1	HV	FT	NA	NA	Prog (Isolated)	3	37.0	6	31	0.370	1.000
6	R2	LV	FT	NA	NA	Prog (Isolated)	3	6.0	6		0.060	1.000
6	R2	HV	FT	NA	NA	Prog (Isolated)	3	6.0	6		0.060	1.000
North: MC												
7	L2	LV	FT	NA	NA	Prog (Isolated)	3	21.0	21		0.210	1.000
7	L2	HV	FT	NA	NA	Prog (Isolated)	3	21.0	21		0.210	1.000
8	T1	LV	FT	NA	NA	Prog (Isolated)	3	21.0	21		0.210	1.000
8	T1	HV	FT	NA	NA	Prog (Isolated)	3	21.0	21		0.210	1.000
9	R2	LV	FT	NA	NA	Prog (Isolated)	3	6.0	6		0.060	1.000
9	R2	HV	FT	NA	NA	Prog (Isolated)	3	6.0	6		0.060	1.000
West: SH												
10	L2	LV	FT	NA	NA	Prog (Isolated)	3	43.0	43		0.430	1.000
10	L2	HV	FT	NA	NA	Prog (Isolated)	3	43.0	43		0.430	1.000
11	T1	LV	FT	NA	NA	Prog (Isolated)	3	43.0	43		0.430	1.000
11	T1	HV	FT	NA	NA	Prog (Isolated)	3	43.0	43		0.430	1.000
12	R2	LV	FT	NA	NA	Prog (Isolated)	3	6.0	6		0.060	1.000
12	R2	HV	FT	NA	NA	Prog (Isolated)	3	6.0	6		0.060	1.000

NA Stopline Distance and Stopline Travel Time parameters are only available for internal approach movements in Network analysis. ACTUATED SIGNAL INFORMATION : Fixed-Time / Pretimed analysis method used.

MOVEMENT CAPACITY AND PERFORMANCE PARAMETERS

Intersection ID: Fixed-Time Signals Cycle Time = 100 sec (Practical Cycle Time)

Table A.9 Movement capacity parameters

Mov ID	Turn	Mov Cl.	Arv Flow veh/h	Satn Flow 1st Grn	Satn Flow 2nd Grn	Flow Ratio 1st Grn	Flow Ratio 2nd Grn	Total Cap. veh/h	Prac. Deg. Satn xp	Prac. Spare Cap. %	Deg. Satn x
South: MC											
1	L2	#	1	4416		0.000		927	0.90	****	0.001
2	T1	#	1	4416		0.000		927	0.90	****	0.001
3	R2	#	1	1625		0.001		98	0.90	8238	0.011
East: SH											
4	L2	#	1	1625		0.001		504	0.90	****	0.002
5	T1	#	1	1726	1726	0.000	0.000	638	0.90	****	0.002
6	R2	#	1	1625		0.001		98	0.90	8238	0.011
North: MC											
7	L2	#	1	1625		0.001		341	0.90	****	0.003
8	T1	#	1	1726		0.001		362	0.90	****	0.003
9	R2	#	1	1445		0.001		87	0.90	7313	0.012*
West: SH											
10	L2	#	1	1445		0.001		621	0.90	****	0.002
11	T1	#	1	1726		0.001		742	0.90	****	0.001
12	R2	#	1	1445		0.001		87	0.90	7313	0.012*
Pedestrian Movements											
P1			53	400		0.132		64	0.90		0.822
P2			53	400		0.132		24	0.90		2.193
P3			53	400		0.132		112	0.90		0.470
P4			53	400		0.132		24	0.90		2.193

* Maximum degree of saturation ; # Combined Movement Capacity parameters are shown for all Movement Classes. The Flow Ratio values given in this table are calculated for signal timing purposes. For movements with two green periods they are subject to balancing as relevant to determining Required Movement Times given in the Movement Timing Information table. Zero values will be given for a slip /bypass lane movement if the option “Exclude Slip/Bypass Lane from Signal Analysis” has been selected.

Table A.10 Movement performance

Mov ID	Turn	Total Delay (veh-h/h)	Total Delay (pers-h/h)	Aver. Delay (sec)	Eff. Stop Rate	Total Stops	Perf. Index	Tot.Trav. Distance (veh-km/h)	Tot.Trav. Time (veh-h/h)	Aver. Speed (km/h)
South: MC										
1	L2	0.01	0.01	38.1	0.54	0.6	0.11	1.1	0.0	36.6
2	T1	0.01	0.01	32.4	0.51	0.5	0.08	1.1	0.0	38.4
3	R2	0.02	0.02	55.2	0.59	0.6	0.10	1.1	0.0	30.9
East: SH										
4	L2	0.01	0.01	30.8	0.60	0.6	0.07	1.1	0.0	38.8
5	T1	0.00	0.00	13.0	0.38	0.4	0.05	1.1	0.0	49.5
6	R2	0.02	0.02	55.2	0.59	0.6	0.10	1.1	0.0	30.9
North: MC										
7	L2	0.01	0.01	38.9	0.60	0.6	0.08	1.1	0.0	35.7
8	T1	0.01	0.01	33.1	0.49	0.5	0.08	1.1	0.0	38.9
9	R2	0.02	0.02	55.8	0.59	0.6	0.10	1.1	0.0	30.6
West: SH										
10	L2	0.01	0.01	23.0	0.60	0.6	0.06	1.1	0.0	41.8
11	T1	0.00	0.01	16.9	0.36	0.4	0.06	1.1	0.0	47.0
12	R2	0.02	0.02	55.8	0.59	0.6	0.10	1.1	0.0	30.6
Pedestrian Movements										
P1		0.55	0.55	37.8	0.90	47.3	1.27	2.1	1.0	2.1
P2		0.69	0.69	47.3	1.01	53.0	1.44	2.1	1.1	1.9
P3		0.41	0.41	27.7	0.77	40.6	1.09	2.1	0.9	2.5
P4		0.69	0.69	47.3	1.01	53.0	1.44	2.1	1.1	1.9

LANE PERFORMANCE AND CAPACITY INFORMATION

Intersection ID: 1
Fixed-Time Signals   Cycle Time = 100 sec (Practical Cycle Time)

Table A.11 Lane performance

Lane No.	Effective Red and Green Times (sec) R1	G1	R2	G2	Arv Flow veh/h	Cap veh/h	Deg. Satn x	Aver. Delay sec	Eff. Stop Rate	Queue 95% Back veh	m	Lane Length m
South: MC												
1	79	21			2	1492	0.001	35.8	0.54	0.1	0.6	500.0
2	79	21			0	362	0.001	32.9	0.46	0.0	0.1	500.0
3	94	6			1	98	0.011	55.2	0.59	0.1	0.4	60.0T
East: SH												
1	69	31			1	504	0.002	30.8	0.60	0.0	0.3	500.0
2	45	6	18	31	1	638	0.002	13.0	0.38	0.0	0.2	500.0
3	94	6			1	98	0.011	55.2	0.59	0.1	0.4	60.0T
North: MC												
1	79	21			1	341	0.003	38.9	0.60	0.0	0.3	500.0
2	79	21			1	362	0.003	33.1	0.49	0.0	0.3	500.0
3	94	6			1	87	0.012	55.8	0.59	0.1	0.5	60.0T
West: SH												
1	57	43			1	621	0.002	23.0	0.60	0.0	0.3	500.0
2	57	43			1	742	0.001	16.9	0.36	0.0	0.2	500.0
3	94	6			1	87	0.012	55.8	0.59	0.1	0.5	60.0T

T Short lane due to specification of Turn Bay

Table A.12 Lane flow and capacity information

Lane No.	Total Arv Flow (veh/h)	Lane Width m	Saturation Flow Adj. Basic (tcu)	Saturation Flow Aver 1st (veh)	Saturation Flow Aver 2nd (veh)	Flow Ratio 1st Grn	Flow Ratio 2nd Grn	End Cap veh/h	Tot Cap veh/h	Deg. Satn x	Lane Util %
South: MC											
1	2	3.30	9000	7107		0.000		0	1492	0.001	100
2	0	3.30	1950	1726		0.000		0	362	0.001	100
3	1	3.30	1950	1625		0.001		0	98	0.011	100
East: SH											
1	1	3.30	1950	1625		0.001		0	504	0.002	100
2	1	3.30	1950	1726	1726	0.001	0.001	0	638	0.002	79P
3	1	3.30	1950	1625		0.001		0	98	0.011	100
North: MC											
1	1	3.30	1950	1625		0.001		0	341	0.003	100
2	1	3.30	1950	1726		0.001		0	362	0.003	94P
3	1	3.30	1950	1445		0.001		0	87	0.012	100
West: SH											
1	1	3.30	1950	1445		0.001		0	621	0.002	100
2	1	3.30	1950	1726		0.001		0	742	0.001	84P
3	1	3.30	1950	1445		0.001		0	87	0.012	100

P Lane under-utilisation found by the Program

Basic Saturation Flow in this table is adjusted for lane width, approach grade, parking manoeuvres and number of buses stopping. Saturation flow scale applies if specified.

Table A.13 Coordination parameters

Lane No.	Deg. Satn x	Arv Flow Rate veh/h	Satn Flow Rate 1st Grn	Satn Flow Rate 2nd Grn	Flow Ratio 1st Grn	Flow Ratio 2nd Grn	Green Ratio 1st Grn	Green Ratio 2nd Grn	% Arv During Green	Pla-toon Ratio	Progression Factors Delay	Progression Factors Queue	Que Clearance 1st Grn	Que Clearance 2nd Grn
South: MC														
1	0.001	2	7107		0.000		0.210		21.0	1.000	1.000	1.000	0.0	
2	0.001	0	1726		0.000		0.210		21.0	1.000	1.000	1.000	0.0	
3	0.011	1	1625		0.001		0.060		6.0	1.000	1.000	1.000	0.1	
East: SH														
1	0.002	1	1625		0.001		0.310		31.0	1.000	1.000	1.000	0.0	
2	0.002	1	1726	1726	0.001	0.001	0.060	0.310	37.0	1.000	1.000	1.000	0.0	0.0
3	0.011	1	1625		0.001		0.060		6.0	1.000	1.000	1.000	0.1	
North: MC														
1	0.003	1	1625		0.001		0.210		21.0	1.000	1.000	1.000	0.1	
2	0.003	1	1726		0.001		0.210		21.0	1.000	1.000	1.000	0.0	
3	0.012	1	1445		0.001		0.060		6.0	1.000	1.000	1.000	0.1	
West: SH														
1	0.002	1	1445		0.001		0.430		43.0	1.000	1.000	1.000	0.0	
2	0.001	1	1726		0.001		0.430		43.0	1.000	1.000	1.000	0.0	
3	0.012	1	1445		0.001		0.060		6.0	1.000	1.000	1.000	0.1	

Table A.14 Lane, approach and intersection performance

Intersection ID: Fixed-Time Signals   Cycle Time = 100 sec (Practical Cycle Time)

Lane No.	Arrival Flow (veh/h)	%HV	Adj. Basic Satf.	Eff Grn (sec) 1st	Eff Grn (sec) 2nd	Deg Sat x	Aver. Delay sec	Longest Queue m	Shrt Lane m
South: MC									
1	2	32	9000	21		0.001	35.8	1	500
2	0	20	1950	21		0.001	32.9	0	500
3	1	20	1950	6		0.011	55.2	0	60
	3	27				0.011	41.9	1	
East: SH									
1	1	20	1950	31		0.002	30.8	0	500
2	1	20	1950	6	31	0.002	13.0	0	500
3	1	20	1950	6		0.011	55.2	0	60
	3	20				0.011	33.0	0	
North: MC									
1	1	20	1950	21		0.003	38.9	0	500
2	1	20	1950	21		0.003	33.1	0	500
3	1	40	1950	6		0.012	55.8	0	60
	3	27				0.012	42.6	0	
West: SH									
1	1	40	1950	43		0.002	23.0	0	500
2	1	20	1950	43		0.001	16.9	0	500
3	1	40	1950	6		0.012	55.8	0	60
	3	33				0.012	31.9	0	
Pedestrians									
P1	53			16		0.822	37.8	4.0	
P2	53			6		2.193	47.3	4.5	
P3	53			28		0.470	27.7	3.5	
P4	53			6		2.193	47.3	4.5	

ALL VEHICLES

Total Flow	% HV	Cycle Time	Max X	Aver. Delay	Max Queue
13	27	100	0.012	37.3	1

Peak flow period = 45 minutes. Queue values in this table are 95% queue (metres)
Note: Basic Saturation Flows (in through car units) have been adjusted for grade, lane widths, parking manoeuvres and bus stops.

Table A.15 Driver characteristics

Intersection ID: 1
Fixed-Time Signals   Cycle Time = 100 sec (Practical Cycle Time)

Lane No.	Satn Speed km/h	Satn Flow veh/h	Satn Hdwy sec	Satn Spacing m	Average Queue Space m	Driver Response Time sec
South: MC						
1	29.6	7107	0.51	4.16	8.95	-0.58
2	45.0	1726	2.09	26.08	8.20	1.43
3	NA - Short Lane					
East: SH						
1	20.2	1625	2.21	12.41	8.20	0.75
2	45.0	1726	2.09	26.08	8.20	1.43
3	NA - Short Lane					
North: MC						
1	20.2	1625	2.21	12.41	8.20	0.75
2	45.0	1726	2.09	26.08	8.20	1.43
3	NA - Short Lane					
West: SH						
1	20.2	1445	2.49	13.95	9.40	0.81
2	45.0	1726	2.09	26.08	8.20	1.43
3	NA - Short Lane					

Table A.16 Flow rates

Intersection ID: 1
Fixed-Time Signals   Cycle Time = 100 sec (Practical Cycle Time)

TOTAL FLOW RATES for All Movement Classes (veh/h)

From SOUTH To:	W	N	E	
Turn:	L2	T1	R2	TOT
Flow Rate	1.1	1.1	1.1	3.2
%HV (all designations)	40.0	20.0	20.0	26.7

From EAST To:	S	W	N	
Turn:	L2	T1	R2	TOT
Flow Rate	1.1	1.1	1.1	3.2
%HV (all designations)	20.0	20.0	20.0	20.0

From NORTH To:	E	S	W	
Turn:	L2	T1	R2	TOT
Flow Rate	1.1	1.1	1.1	3.2
%HV (all designations)	20.0	20.0	40.0	26.7

From WEST To:	N	E	S	
Turn:	L2	T1	R2	TOT
Flow Rate	1.1	1.1	1.1	3.2
%HV (all designations)	40.0	20.0	40.0	33.3

Flow rates shown above are Arrival Flow Rates (veh/h) based on the following input specifications:
Unit Time for Volumes = 60 minutes
Peak Flow Period = 45 minutes
Effects of Volume Factors (Peak Flow Factor, Flow Scale, Growth Rate) are included.
Arrival Flow Rates may be less than Demand Flow Rates if capacity constraint applies in network analysis.

Table A.17 Origin-Destination Flow Rates by Movement Class

Intersection ID: 1
Fixed-Time Signals   Cycle Time = 100 sec (Practical Cycle Time)

FLOW RATES for Light Vehicles (veh/h)

From SOUTH To:	W	N	E	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.6	0.8	0.8	2.3
Mov Class %	60.0	80.0	80.0	73.3
Residual Demand	0.0	0.0	0.0	0.0

From EAST To:	S	W	N	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.8	0.8	0.8	2.5
Mov Class %	80.0	80.0	80.0	80.0
Residual Demand	0.0	0.0	0.0	0.0

From NORTH To:	E	S	W	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.8	0.8	0.6	2.3
Mov Class %	80.0	80.0	60.0	73.3
Residual Demand	0.0	0.0	0.0	0.0

From WEST To:	N	E	S	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.6	0.8	0.6	2.1
Mov Class %	60.0	80.0	60.0	66.7
Residual Demand	0.0	0.0	0.0	0.0

Table A.18 FLOW RATES for Heavy Vehicles (veh/h)

From SOUTH To:	W	N	E	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.4	0.2	0.2	0.8
Mov Class %	40.0	20.0	20.0	26.7
Residual Demand	0.0	0.0	0.0	0.0

From EAST To:	S	W	N	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.2	0.2	0.2	0.6
Mov Class %	20.0	20.0	20.0	20.0
Residual Demand	0.0	0.0	0.0	0.0

From NORTH To:	E	S	W	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.2	0.2	0.4	0.8
Mov Class %	20.0	20.0	40.0	26.7
Residual Demand	0.0	0.0	0.0	0.0

From WEST To:	N	E	S	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.4	0.2	0.4	1.1
Mov Class %	40.0	20.0	40.0	33.3
Residual Demand	0.0	0.0	0.0	0.0

Flow rates shown above are Arrival Flow Rates (veh/h) based on the following input specifications:
Unit Time for Volumes = 60 minutes
Peak Flow Period = 45 minutes
Effects of Volume Factors (Peak Flow Factor, Flow Scale, Growth Rate) are included.
Arrival Flow Rates may be less than Demand Flow Rates if capacity constraint applies in network analysis.

Intersection ID: 1
Fixed-Time Signals   Cycle Time = 100 sec (Practical Cycle Time)

Table A.19 Lane flow rates at stop line (veh/h)

From SOUTH To:	W	N	E	
Turn:	L2	T1	R2	TOT
Lane 1				
LV	0.6	0.5	*	1.1
HV	0.4	0.1	*	0.5
Total	1.1	0.6	*	1.7
Lane 2				
LV	*	0.3	*	0.3
HV	*	0.1	*	0.1
Total	*	0.4	*	0.4
Lane 3				
LV	*	*	0.8	0.8
HV	*	*	0.2	0.2
Total	*	*	1.1	1.1
Approach	1.1	1.1	1.1	3.2

From EAST To:	S	W	N	
Turn:	L2	T1	R2	TOT
Lane 1				
LV	0.8	*	*	0.8
HV	0.2	*	*	0.2
Total	1.1	*	*	1.1
Lane 2				
LV	*	0.8	*	0.8
HV	*	0.2	*	0.2
Total	*	1.1	*	1.1
Lane 3				
LV	*	*	0.8	0.8
HV	*	*	0.2	0.2
Total	*	*	1.1	1.1

Approach	1.1	1.1	1.1	3.2

From NORTH To:	E	S	W	
Turn:	L2	T1	R2	TOT
Lane 1				
LV	0.8	*	*	0.8
HV	0.2	*	*	0.2
Total	1.1	*	*	1.1
Lane 2				
LV	*	0.8	*	0.8
HV	*	0.2	*	0.2
Total	*	1.1	*	1.1
Lane 3				
LV	*	*	0.6	0.6
HV	*	*	0.4	0.4
Total	*	*	1.1	1.1
Approach	1.1	1.1	1.1	3.2

From WEST To:	N	E	S	
Turn:	L2	T1	R2	TOT
Lane 1				
LV	0.6	*	*	0.6
HV	0.4	*	*	0.4
Total	1.1	*	*	1.1
Lane 2				
LV	*	0.8	*	0.8
HV	*	0.2	*	0.2
Total	*	1.1	*	1.1
Lane 3				
LV	*	*	0.6	0.6
HV	*	*	0.4	0.4
Total	*	*	1.1	1.1
Approach	1.1	1.1	1.1	3.2

* Movement not allocated to the lane

Table A.20 Exit lane flow rates

Movement Class:	LV	HV	B	C	TR	LR	U1	U2	TOT
Exit: SOUTH									
Lane: 1	0.8	0.2	*	*	*	*	*	*	1.1
Lane: 2	1.5	0.6	*	*	*	*	*	*	2.1
Total	2.3	0.8	*	*	*	*	*	*	3.2
Exit: EAST									
Lane: 1	0.8	0.2	*	*	*	*	*	*	1.1
Lane: 2	1.7	0.4	*	*	*	*	*	*	2.1
Total	2.5	0.6	*	*	*	*	*	*	3.2
Exit: NORTH									
Lane: 1	1.1	0.5	*	*	*	*	*	*	1.7
Lane: 2	1.2	0.3	*	*	*	*	*	*	1.5
Total	2.3	0.8	*	*	*	*	*	*	3.2
Exit: WEST									
Lane: 1	0.6	0.4	*	*	*	*	*	*	1.1
Lane: 2	1.5	0.6	*	*	*	*	*	*	2.1
Total	2.1	1.1	*	*	*	*	*	*	3.2

* Movement not allocated to the lane

Table A.21 Downstream lane flow rates for exit roads

Movement Class:	LV	HV	B	C	TR	LR	U1	U2	TOT
Exit: SOUTH									
Lane: 1	0.8	0.2	*	*	*	*	*	*	1.1
Lane: 2	1.5	0.6	*	*	*	*	*	*	2.1
Total	2.3	0.8	*	*	*	*	*	*	3.2
Exit: EAST									
Lane: 1	0.8	0.2	*	*	*	*	*	*	1.1
Lane: 2	1.7	0.4	*	*	*	*	*	*	2.1
Total	2.5	0.6	*	*	*	*	*	*	3.2
Exit: NORTH									
Lane: 1	1.1	0.5	*	*	*	*	*	*	1.7
Lane: 2	1.2	0.3	*	*	*	*	*	*	1.5
Total	2.3	0.8	*	*	*	*	*	*	3.2
Exit: WEST									
Lane: 1	0.6	0.4	*	*	*	*	*	*	1.1
Lane: 2	1.5	0.6	*	*	*	*	*	*	2.1
Total	2.1	1.1	*	*	*	*	*	*	3.2

* Movement not allocated to the lane

Flow rates shown above are Arrival Flow Rates (veh/h) based on the following input specifications:
Unit Time for Volumes = 60 minutes
Peak Flow Period = 45 minutes
Effects of Volume Factors (Peak Flow Factor, Flow Scale, Growth Rate) are included.
Arrival Flow Rates may be less than Demand Flow Rates if capacity constraint applies in network analysis.

Table A.22 Sensitivity Analysis Results

```
Intersection ID: 1
 Fixed-Time Signals   Cycle Time = 100 sec (Practical Cycle Time)

 Scaled sensitivity parameter: Fol.up Hdway and Crit Gap
   Degree of saturation = 0.012 was achieved at parameter scale =  80.0 %
   All scaled parameter values gave degree of saturation less than 1.0.
   Try adjusting the scale factor range to give higher degrees of saturation.


 Results in the table below are given for Intersection - Vehicles
```

Param Scale (%)	Cycle Time (sec)	Eff. Cap.	Degree of Satn	Prac. Spare Cap.	Aver. Delay (sec)	Stop Rate	95% Back of Queue (veh)	Perf. Index	Cost Total $/h
80.0	100	1040	0.012	7313	37.3	0.54	0.1	1.0	324.0
85.0	100	1040	0.012	7313	37.3	0.54	0.1	1.0	324.0
90.0	100	1040	0.012	7313	37.3	0.54	0.1	1.0	324.0
95.0	100	1040	0.012	7313	37.3	0.54	0.1	1.0	324.0
100.0	100	1040	0.012	7313	37.3	0.54	0.1	1.0	324.0
105.0	100	1040	0.012	7313	37.3	0.54	0.1	1.0	324.0
110.0	100	1040	0.012	7313	37.3	0.54	0.1	1.0	324.0
115.0	100	1040	0.012	7313	37.3	0.54	0.1	1.0	324.0
120.0	100	1040	0.012	7313	37.3	0.54	0.1	1.0	324.0

Conversion to a roundabout:

If the above signalised intersection is converted into a roundabout, it will be having the following parameters, with the layout shown in Figure A.2.

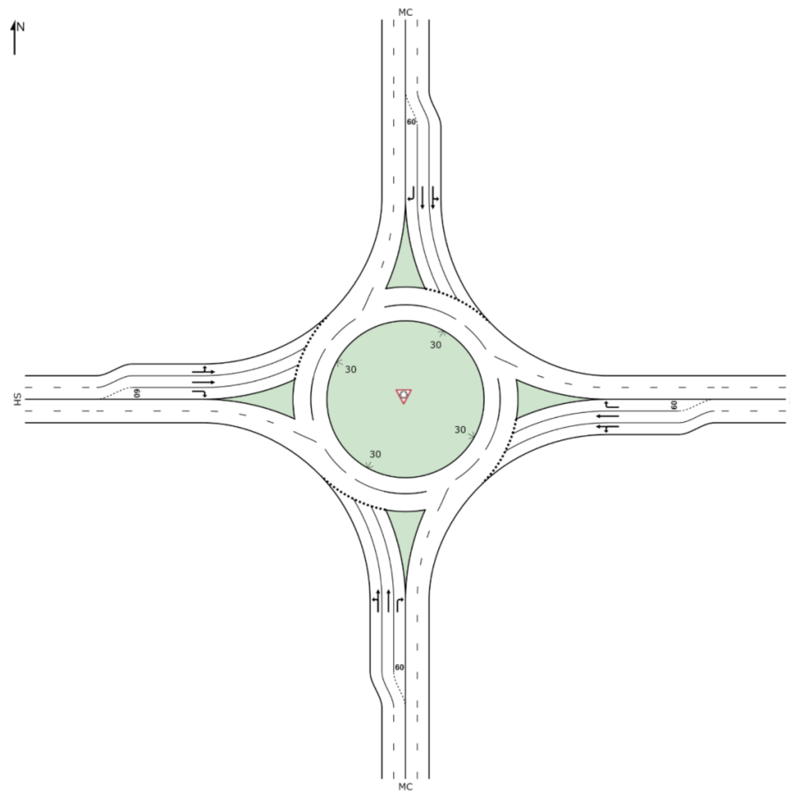

Figure A.2 Conversion of signalised intersection to Roundabout

Basic Parameters:

- Intersection Type: Roundabout
- Input data specified in Metric units
- Peak Flow Period (for performance): 45 minutes
- SIDRA Standard Delay model used
- Level of Service based on: Delay (HCM 2000)

Driving on the left-hand side of the road

Model Defaults: Standard Left

Unit time (for volumes): 60 minutes.

SIDRA Standard Queue model used

Queue percentile: 95%

Intersection ID: 1

Table A.23 Roundabout basic parameters

Central Island Diam m	Circ Width m	Insc Diam. m	Entry Radius m	Entry Angle deg	Circ Lanes	Entry Lanes	Av.Entry Lane Width m
South: MC							
30.0	10.0	50.0	20.0	30.0	2	3	3.30
East: SH							
30.0	10.0	50.0	20.0	30.0	2	3	3.30
North: MC							
30.0	10.0	50.0	20.0	30.0	2	3	3.30
West: SH							
30.0	10.0	50.0	20.0	30.0	2	3	3.30

Roundabout Capacity Model: SIDRA Standard

Table A. 24 Roundabout circulating and exiting stream parameters

Intersection ID: 1
Roundabout

Dest	Turn	Lane No.	Lane Type	Opng Flow veh/h	HVE pcu/ veh	Adj. Flow pcu/h	%Near Lane Only	%Exit Flow Incl.	Cap. Const. Effect	O-D Factor	Aver Speed km/h	In-Bunch Headway sec	Prop. Bunched
South: MC													
W	L2	1	Dominant	3	1.13	4	0.0	0.0	N	1.000	30.2	1.26	0.003
N	T1	1	Dominant	3	1.13	4	0.0	0.0	N	1.000	30.2	1.26	0.003
N	T1	2	Subdominant	3	1.13	4	0.0	0.0	N	1.000	30.2	1.26	0.003
E	R2	3	Subdominant	3	1.13	4	0.0	0.0	N	1.000	30.2	1.26	0.003
East: SH													
S	L2	1	Dominant	3	1.17	4	0.0	0.0	N	1.000	30.2	1.27	0.003
W	T1	1	Dominant	3	1.17	4	0.0	0.0	N	1.000	30.2	1.27	0.003
W	T1	2	Subdominant	3	1.17	4	0.0	0.0	N	1.000	30.2	1.27	0.003
N	R2	3	Subdominant	3	1.17	4	0.0	0.0	N	1.000	30.2	1.27	0.003
North: MC													
E	L2	1	Dominant	3	1.13	4	0.0	0.0	N	1.000	30.2	1.26	0.003
S	T1	1	Dominant	3	1.13	4	0.0	0.0	N	1.000	30.2	1.26	0.003
S	T1	2	Subdominant	3	1.13	4	0.0	0.0	N	1.000	30.2	1.26	0.003
W	R2	3	Subdominant	3	1.13	4	0.0	0.0	N	1.000	30.2	1.26	0.003
West: SH													
N	L2	1	Dominant	3	1.10	3	0.0	0.0	N	1.000	30.2	1.24	0.003
E	T1	1	Dominant	3	1.10	3	0.0	0.0	N	1.000	30.2	1.24	0.003
E	T1	2	Subdominant	3	1.10	3	0.0	0.0	N	1.000	30.2	1.24	0.003
S	R2	3	Subdominant	3	1.10	3	0.0	0.0	N	1.000	30.2	1.24	0.003

Roundabout Capacity Model: SIDRA Standard

Table A.25 Roundabout gap acceptance parameters

Intersection ID: 1 Roundabout

Dest	Turn	Lane No.	Lane Type	In-Bunch Headway sec	Prop. Bunched	Priority Sharing	HVE for Entry	Critical Gap Headway sec	Critical Gap Dist m	Follow-up Headway sec
South: MC										
Environment Factor: 1.00										
Entry/Circ. Flow Adjustment: Medium										
W	L2	1	Dominant	1.26	0.003	N	1.20	5.52	46.3	2.88
N	T1	1	Dominant	1.26	0.003	N	1.10	5.06	42.4	2.64
N	T1	2	Subdominant	1.26	0.003	N	1.10	5.85	49.0	3.05
E	R2	3	Subdominant	1.26	0.003	N	1.10	5.84	48.9	3.04
East: SH										
Environment Factor: 1.00										
Entry/Circ. Flow Adjustment: Medium										
S	L2	1	Dominant	1.27	0.003	N	1.10	5.06	42.4	2.64
W	T1	1	Dominant	1.27	0.003	N	1.10	5.06	42.4	2.64
W	T1	2	Subdominant	1.27	0.003	N	1.10	5.89	49.4	3.07
N	R2	3	Subdominant	1.27	0.003	N	1.10	5.85	49.1	3.05
North: MC										
Environment Factor: 1.00										
Entry/Circ. Flow Adjustment: Medium										
E	L2	1	Dominant	1.26	0.003	N	1.10	5.06	42.4	2.64
S	T1	1	Dominant	1.26	0.003	N	1.10	5.06	42.4	2.64
S	T1	2	Subdominant	1.26	0.003	N	1.10	5.89	49.4	3.07
W	R2	3	Subdominant	1.26	0.003	N	1.20	6.38	53.6	3.33
West: SH										
Environment Factor: 1.00										
Entry/Circ. Flow Adjustment: Medium										
N	L2	1	Dominant	1.24	0.003	N	1.20	5.52	46.3	2.88
E	T1	1	Dominant	1.24	0.003	N	1.10	5.06	42.4	2.64
E	T1	2	Subdominant	1.24	0.003	N	1.10	5.85	49.0	3.05
S	R2	3	Subdominant	1.24	0.003	N	1.20	6.37	53.4	3.32

Roundabout Capacity Model: SIDRA Standard

Dist (Distance): Spacing, i.e. distance between the front ends of two successive vehicles across all lanes in the circulating or exiting stream

Roundabout Flow Rates

Intersection ID: 1
Roundabout

Table A.26 Roundabout circulating lane flow rates

Lane No.	Circulating Flow Rates veh/h	pcu/h	Percent
South: MC			
1	1	1	32.4%
2	2	2	67.6%
Total	3	3	
East: SH			
1	1	1	31.4%
2	2	3	68.6%
Total	3	4	
North: MC			
1	1	1	32.4%
2	2	2	67.6%
Total	3	3	
West: SH			
1	1	1	33.3%
2	2	2	66.7%
Total	3	3	

Table A.27 Approach lane flow rates

Lane No.	Approach Flows (veh/h) Out	To Downst	Total
South: MC			
1	1	0	1
2	0	1	1
3	0	1	1
Total	1	2	3
East: SH			
1	1	0	1
2	0	1	1
3	0	1	1
Total	1	2	3
North: MC			
1	1	0	1
2	0	1	1
3	0	1	1
Total	1	2	3
West: SH			
1	1	0	1
2	0	1	1
3	0	1	1
Total	1	2	3

Intersection Negotiation and Travel Data

Intersection ID: 1
Roundabout

Table A.28 Travel speed, travel distance and travel time

From Approach	To Exit	Turn	Running Speed km/h	Travel Speed km/h	Travel Distance m	Travel Time s	Total Travel Distance Dem Flows veh-km/h	Total Travel Distance Arv Flows veh-km/h	Tot.Trav. Time veh-h/h
South: MC									
	West	L2	55.1	55.1	1020.5#	66.7#	1.1	1.1	0.0
	North	T1	58.0	58.0	1046.3#	64.9#	1.1	1.1	0.0
	East	R2	53.5	53.5	1074.6#	72.3#	1.1	1.1	0.0
East: SH									
	South	L2	55.6	55.6	1021.4#	66.1#	1.1	1.1	0.0
	West	T1	58.0	58.0	1045.2#	64.9#	1.1	1.1	0.0
	North	R2	53.5	53.5	1074.6#	72.3#	1.1	1.1	0.0
North: MC									
	East	L2	55.6	55.6	1021.4#	66.1#	1.1	1.1	0.0
	South	T1	58.0	58.0	1045.2#	64.9#	1.1	1.1	0.0
	West	R2	52.9	52.9	1074.6#	73.2#	1.1	1.1	0.0
West: SH									
	North	L2	55.1	55.1	1020.5#	66.7#	1.1	1.1	0.0
	East	T1	58.0	58.0	1046.3#	64.9#	1.1	1.1	0.0
	South	R2	52.9	52.9	1074.6#	73.2#	1.1	1.1	0.0
ALL VEHICLES:			55.5	55.4	1047.1#	68.0#	13.2	13.2	0.2

"Running Speed" is the average speed excluding stopped periods.

Travel Time values include cruise times and intersection delays including acceleration, deceleration and idling delays.

Travel Distance and Travel Time values include travel on the External Exit section based on the program-determined Exit Distance or user-specified Downstream Distance as applicable.

Table A.29 Intersection negotiation data

From Approach	To Exit	Turn	Negn Radius m	Negn Speed km/h	Negn Dist. m	Appr. Dist. m	Exit Dist. m	Downstr. Dist. m
South: MC								
	West	L2	33.1	31.8	19.4	500	500	NA
	North	T1	57.3	39.1	47.1	500	500	NA
	East	R2	19.0	25.7	74.6	500	500	NA
East: SH								
	South	L2	33.1	31.8	19.4	500	500	NA
	West	T1	57.3	39.1	47.1	500	500	NA
	North	R2	19.0	25.7	74.6	500	500	NA
North: MC								
	East	L2	33.1	31.8	19.4	500	500	NA
	South	T1	57.3	39.1	47.1	500	500	NA
	West	R2	19.0	25.7	74.6	500	500	NA
West: SH								
	North	L2	33.1	31.8	19.4	500	500	NA
	East	T1	57.3	39.1	47.1	500	500	NA
	South	R2	19.0	25.7	74.6	500	500	NA

Maximum Negotiation (Design) Speed = 50.0 km/h

NA Downstream Distance does not apply if:
- Exit is an internal leg of a network
- "Program" option was specified
- Distance specified was less than the Exit Negotiation Distance
- Distance specified was greater than the exit leg length

Table A.30 Movement speeds and geometric delay

Mov ID	Turn	App. Speeds Cruise km/h	App. Speeds Negn km/h	Exit Speeds Negn km/h	Exit Speeds Cruise km/h	Queue Move-up Speed km/h	Geom Delay sec
South: MC							
1	L2	60.0	31.8	31.8	60.0	32.0	4.1
2	T1	60.0	39.1	39.1	60.0	38.9	3.7
3	R2	60.0	25.7	25.7	60.0	25.7	9.4
East: SH							
4	L2	60.0	31.8	31.8	60.0	32.3	3.9
5	T1	60.0	39.1	39.1	60.0	38.6	3.7
6	R2	60.0	25.7	25.7	60.0	25.7	9.4
North: MC							
7	L2	60.0	31.8	31.8	60.0	32.3	3.9
8	T1	60.0	39.1	39.1	60.0	38.6	3.7
9	R2	60.0	25.7	25.7	60.0	25.7	9.6
West: SH							
10	L2	60.0	31.8	31.8	60.0	32.0	4.1
11	T1	60.0	39.1	39.1	60.0	38.9	3.7
12	R2	60.0	25.7	25.7	60.0	25.7	9.6

Movement Capacity and Performance Parameters

Intersection ID: 1
Roundabout

Table A.31 Movement capacity parameters

Mov ID	Turn	Mov Cl.	Arv Flow veh/h	Opng Flow veh/h	Movement Adjust. Flow pcu/h	Total Cap. veh/h	Prac. Deg. Satn xp	Prac. Spare Cap. %	Deg. Satn x
South: MC									
1	L2	#	1	3	4	1212	0.85	****	0.001*
2	T1	#	1	6	7	1212	0.85	****	0.001*
3	R2	#	1	3	4	1178	0.85	****	0.001*
East: SH									
4	L2	#	1	3	4	1264	0.85	****	0.001*
5	T1	#	1	6	7	1264	0.85	****	0.001*
6	R2	#	1	3	4	1174	0.85	****	0.001*
North: MC									
7	L2	#	1	3	4	1264	0.85	****	0.001*
8	T1	#	1	6	7	1264	0.85	****	0.001*
9	R2	#	1	3	4	1076	0.85	****	0.001*
West: SH									
10	L2	#	1	3	3	1212	0.85	****	0.001*
11	T1	#	1	6	7	1212	0.85	****	0.001*
12	R2	#	1	3	3	1079	0.85	****	0.001*

* Maximum degree of saturation
# Combined Movement Capacity parameters are shown for all Movement Classes.

The Flow Ratio values given in this table are calculated for signal timing purposes. For movements with two green periods they are subject to balancing as relevant to determining Required Movement Times given in the Movement Timing Information table. Zero values will be given for a slip /bypass lane movement if the option "Exclude Slip/Bypass Lane from Signal Analysis" has been selected.

Table A.32 Movement performance

Mov ID	Turn	Total Delay (veh-h/h)	Total Delay (pers-h/h)	Aver. Delay (sec)	Eff. Stop Rate	Total Stops	Perf. Index	Tot.Trav. Distance (veh-km/h)	Tot.Trav. Time (veh-h/h)	Aver. Speed (km/h)
South: MC										
1	L2	0.00	0.00	4.1	0.43	0.5	0.02	1.1	0.0	55.1
2	T1	0.00	0.00	3.7	0.34	0.4	0.02	1.1	0.0	58.0
3	R2	0.00	0.00	9.4	0.62	0.6	0.03	1.1	0.0	53.5
East: SH										
4	L2	0.00	0.00	3.9	0.43	0.5	0.02	1.1	0.0	55.6
5	T1	0.00	0.00	3.7	0.34	0.4	0.02	1.1	0.0	58.0
6	R2	0.00	0.00	9.4	0.62	0.6	0.03	1.1	0.0	53.5
North: MC										
7	L2	0.00	0.00	3.9	0.43	0.5	0.02	1.1	0.0	55.6
8	T1	0.00	0.00	3.7	0.34	0.4	0.02	1.1	0.0	58.0
9	R2	0.00	0.00	9.6	0.60	0.6	0.03	1.1	0.0	52.9
West: SH										
10	L2	0.00	0.00	4.1	0.43	0.5	0.02	1.1	0.0	55.1
11	T1	0.00	0.00	3.7	0.34	0.4	0.02	1.1	0.0	58.0
12	R2	0.00	0.00	9.6	0.60	0.6	0.03	1.1	0.0	52.9

Lane Performance and Capacity Information

Intersection ID: 1

Roundabout

Table A.33 Lane performance

Lane No.	Flow veh/h	Cap veh/h	Deg. Satn x	Aver. Delay sec	Eff. Stop Rate	Queue 95% Back veh	Queue 95% Back m	Lane Length m
South: MC								
1	1	1248	0.001	4.1	0.43	0.0	0.0	500.0
2	1	1175	0.001	3.7	0.34	0.0	0.0	500.0
3	1	1178	0.001	9.4	0.62	0.0	0.0	60.0T
East: SH								
1	1	1359	0.001	3.9	0.43	0.0	0.0	500.0
2	1	1168	0.001	3.7	0.34	0.0	0.0	500.0
3	1	1174	0.001	9.4	0.62	0.0	0.0	60.0T
North: MC								
1	1	1359	0.001	3.9	0.43	0.0	0.0	500.0
2	1	1168	0.001	3.7	0.34	0.0	0.0	500.0
3	1	1076	0.001	9.6	0.60	0.0	0.0	60.0T
West: SH								
1	1	1249	0.001	4.1	0.43	0.0	0.0	500.0
2	1	1175	0.001	3.7	0.34	0.0	0.0	500.0
3	1	1079	0.001	9.6	0.60	0.0	0.0	60.0T

T Short lane due to specification of Turn Bay

Table A.34 Lane flow and capacity information

Lane No.	Total Arv Flow (veh/h)	Min Cap veh/h	Tot Cap veh/h	Deg. Satn x	Lane Util %
South: MC					
1	1	1	1248	0.001	100
2	1	1	1175	0.001	100
3	1	1	1178	0.001	100
East: SH					
1	1	1	1359	0.001	100
2	1	1	1168	0.001	100
3	1	1	1174	0.001	100
North: MC					
1	1	1	1359	0.001	100
2	1	1	1168	0.001	100
3	1	1	1076	0.001	100
West: SH					
1	1	1	1249	0.001	100
2	1	1	1175	0.001	100
3	1	1	1079	0.001	100

The capacity value for priority and continuous movements is obtained by adjusting the basic saturation flow for heavy vehicle and turning vehicle effects. Saturation flow scale applies if specified.

Table A.35 Lane, Approach and Intersection Performance

Intersection ID: 1 Roundabout

Lane No.	Arrival Flow (veh/h)	%HV	Adj. Basic Satf.	Deg Sat x	Aver. Delay sec	Longest Queue m	Shrt Lane m
South: MC							
1	1	39		0.001	4.1	0	500
2	1	20		0.001	3.7	0	500
3	1	20		0.001	9.4	0	60
	3	27		0.001	5.7	0	
East: SH							
1	1	20		0.001	3.9	0	500
2	1	20		0.001	3.7	0	500
3	1	20		0.001	9.4	0	60
	3	20		0.001	5.7	0	
North: MC							
1	1	20		0.001	3.9	0	500
2	1	20		0.001	3.7	0	500
3	1	40		0.001	9.6	0	60
	3	27		0.001	5.7	0	
West: SH							
1	1	39		0.001	4.1	0	500
2	1	20		0.001	3.7	0	500
3	1	40		0.001	9.6	0	60
	3	33		0.001	5.8	0	

ALL VEHICLES

Total Flow	% HV	Max X	Aver. Delay	Max Queue
13	27	0.001	5.7	0

Peak flow period = 45 minutes. Queue values in this table are 95% queue (metres)

Note: Basic Saturation Flows are not adjusted at roundabouts or sign controlled intersections and apply only to continuous lanes.

Table A.36 Driver Characteristics

Intersection ID: 1
Roundabout

Lane No.	Satn Speed km/h	Satn Flow veh/h	Satn Hdwy sec	Satn Spacing m	Average Queue Space m	Driver Response Time sec
South: MC						
1	32.0	1254	2.87	25.52	9.36	1.82
2	39.1	1180	3.05	33.14	8.20	2.30
3	NA - Short Lane					
East: SH						
1	32.3	1365	2.64	23.67	8.20	1.72
2	39.1	1172	3.07	33.36	8.20	2.32
3	NA - Short Lane					
North: MC						
1	32.3	1365	2.64	23.67	8.20	1.72
2	39.1	1172	3.07	33.36	8.20	2.32
3	NA - Short Lane					
West: SH						
1	32.0	1254	2.87	25.52	9.36	1.82
2	39.1	1180	3.05	33.14	8.20	2.30
3	NA - Short Lane					

Saturation Flow and Saturation Headway are derived from follow-up headway.

Origin-Destination Flow Rates (Total)

Intersection ID: 1
Roundabout

Table A.37 Total flow rates for All Movement Classes (veh/h)

From SOUTH To:	W	N	E	
Turn:	L2	T1	R2	TOT
Flow Rate	1.1	1.1	1.1	3.2
%HV (all designations)	40.0	20.0	20.0	26.7
From EAST To:	S	W	N	
Turn:	L2	T1	R2	TOT
Flow Rate	1.1	1.1	1.1	3.2
%HV (all designations)	20.0	20.0	20.0	20.0
From NORTH To:	E	S	W	
Turn:	L2	T1	R2	TOT
Flow Rate	1.1	1.1	1.1	3.2
%HV (all designations)	20.0	20.0	40.0	26.7
From WEST To:	N	E	S	
Turn:	L2	T1	R2	TOT
Flow Rate	1.1	1.1	1.1	3.2
%HV (all designations)	40.0	20.0	40.0	33.3

Flow rates shown above are Arrival Flow Rates (veh/h) based on the following input specifications:
Unit Time for Volumes = 60 minutes
Peak Flow Period = 45 minutes
Effects of Volume Factors (Peak Flow Factor, Flow Scale, Growth Rate) are included.
Arrival Flow Rates may be less than Demand Flow Rates if capacity constraint applies in network analysis.

Origin-Destination Flow Rates by Movement Class

Intersection ID: 1
Roundabout

Table A .38 Flow rates for light vehicles (veh/h)

From SOUTH To:	W	N	E	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.6	0.8	0.8	2.3
Mov Class %	60.0	80.0	80.0	73.3
Residual Demand	0.0	0.0	0.0	0.0

From EAST To:	S	W	N	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.8	0.8	0.8	2.5
Mov Class %	80.0	80.0	80.0	80.0
Residual Demand	0.0	0.0	0.0	0.0

From NORTH To:	E	S	W	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.8	0.8	0.6	2.3
Mov Class %	80.0	80.0	60.0	73.3
Residual Demand	0.0	0.0	0.0	0.0

From WEST To:	N	E	S	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.6	0.8	0.6	2.1
Mov Class %	60.0	80.0	60.0	66.7
Residual Demand	0.0	0.0	0.0	0.0

Table A.39 Flow rates for Heavy Vehicles (veh/h)

From SOUTH To:	W	N	E	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.4	0.2	0.2	0.8
Mov Class %	40.0	20.0	20.0	26.7
Residual Demand	0.0	0.0	0.0	0.0

From EAST To:	S	W	N	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.2	0.2	0.2	0.6
Mov Class %	20.0	20.0	20.0	20.0
Residual Demand	0.0	0.0	0.0	0.0

From NORTH To:	E	S	W	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.2	0.2	0.4	0.8
Mov Class %	20.0	20.0	40.0	26.7
Residual Demand	0.0	0.0	0.0	0.0

From WEST To:	N	E	S	
Turn:	L2	T1	R2	TOT
Flow Rate - Veh	0.4	0.2	0.4	1.1
Mov Class %	40.0	20.0	40.0	33.3
Residual Demand	0.0	0.0	0.0	0.0

Flow rates shown above are Arrival Flow Rates (veh/h) based on the following input specifications:
Unit Time for Volumes = 60 minutes
Peak Flow Period = 45 minutes
Effects of Volume Factors (Peak Flow Factor, Flow Scale, Growth Rate) are included.
Arrival Flow Rates may be less than Demand Flow Rates if capacity constraint applies in network analysis.

Table A.40 Sensitivity Analysis Results

Intersection ID: 1
Roundabout

Scaled sensitivity parameter: Fol.up Hdway and Crit Gap
Degree of saturation = 0.001 was achieved at parameter scale = 120.0 %
All scaled parameter values gave degree of saturation less than 1.0.
Try adjusting the scale factor range to give higher degrees of saturation.

Results in the table below are given for Intersection - Vehicles

Param Scale (%)	Eff. Cap.	Degree of Satn	Prac. Spare Cap.	Aver. Delay (sec)	Stop Rate	95% Back of Queue (veh)	Perf. Index	Cost Total $/h
80.0	19397	0.001	130426	5.7	0.46	0.0	0.3	245.0
85.0	18252	0.001	122724	5.7	0.46	0.0	0.3	245.1
90.0	17235	0.001	115877	5.7	0.46	0.0	0.3	245.2
95.0	16325	0.001	109752	5.7	0.46	0.0	0.3	245.2
100.0	15505	0.001	104239	5.7	0.46	0.0	0.3	245.3
105.0	14764	0.001	99251	5.7	0.46	0.0	0.3	245.3
110.0	14090	0.001	94716	5.7	0.46	0.0	0.3	245.4
115.0	13475	0.001	90576	5.7	0.46	0.0	0.3	245.4
120.0	12911	0.001	86780	5.7	0.46	0.0	0.3	245.4

CURRICULUM VITAE
of
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1. CAREER OVERVIEW

- Experienced in Engineering projects, Research and teaching in areas related to Civil Engineering, Transportation, Health & Safety, Hydrology and Water Resources Engineering.
- Master's Degree in Civil Engineering with specialization in Hydrology and Water Resources Engineering
- Experience in planning, design, supervision and quality control of Civil Engineering Projects
- Experience in preparation of EIA.
- Total experience: Industry: 6 years Teaching: 13 years Research: 2 years

2. ACADEMIC QUALIFICATIONS

- Master of Engineering in Civil Engineering (2007), First Rank College of Engineering, Guindy, Anna University, Chennai, India Specialization: Hydrology and Water Resources Engineering. Dissertation: Impact of coastal aquifer development on Submarine Ground Water Discharge

- Bachelor of Technology in Civil Engineering (1995), First Class, NSS College of Engineering, Palakkad, University of Calicut, India.

3. EMPLOYMENT

- Lecturer, Built and Natural Environment Department, Caledonian College of Engineering, Muscat, Oman (Continuing from 01.08. 2010)

- Lecturer, Department of Health, Safety, Environment and Management, International College of Engineering and Management (Fire Safety College), Oman. (2008 October-2010 July)
- Assistant Professor, Department of Civil Engineering, Amal Jyothi College of Engineering, Kanjirapally, Kottayam (2007 August- 2008 October)
- M.E.student/ Teaching Research Associate, Anna University, Chennai (2005July- 2007 July)
- Copy Editor, Sify Ltd., Tidel Park, Chennai (2004 August- 2005 October)
- Lecturer, Department of Civil Engineering, Rajiv Gandhi Institute of Technology, Velloor, Kottayam (2000 July- 2004 August)
- Project Engineer, Skyline Builders, Kottayam (1999 June- 2000 September)
- Project Engineer, A2Z Builders, Ernakulam (1997 September- 1999 May)
- Assistant Engineer, Spades Engineers (P) Ltd., Kozhikode (1995 March- 1997 August)

4. AREAS OF RESEARCH INTEREST

- Health and Safety, EIA, Alternative Energy, Pollution

5. PROFESSIONAL EXPERIENCE

- Managed the construction of multi-storied apartments/ commercial centre.
- Scheduling and planning of the operations.
- Designing and detailing of the structural elements.
- Designing and implementing the water conservation/ waste management structures.
- Assessing the Risk/ considering the safety of Operations in various structures
- Surveying, preparing contour maps for various projects.

6. MAJOR TECHNICAL REPORTS

- Assisted in the preparation of EIA Report of Androth Airport, India.
- Assisted in the analysis of Groundwater conditions in Kerala, prepared as a part of “Palathulli” project of Malayala Manorama.

7. PROFESSIONAL MEMBERSHIPS

- Life Member, Indian Society for Technical Education

- Chartered Engineer, Institution of Engineers (India)
- Associate Member, American Society of Civil Engineers.

8. MAJOR STAFF DEVELOPMENT WORKSHOPS ATTENDED:

- "International Conference on Urban Heritage and architeture", held in Muscat, Oman in 2012.
- “Workshop on Externally funded projects” at Amal Jyothi College of Engineering, Kanjirappally (18/01/2008)
- “Workshop on Appraisal, Monitoring and Evaluation of Projects”, Centre for Development Studies, Thiruvananthapuram (14/05/2008 to 21/05/2008)
- “Excellence in Technical Education through Innovation”, Manipal Institute of Technology, Manipal (17/12/2007 to 19/12/2007)
- “Water Conservation and Watershed Management”, Cochin University of Science and Technology, Kochi (01/03/2004 to 12/03/2004)
- Computer hardware and maintenance- (14 days) – RIT, Kottayam.
- Vastuvidya- (2 days) - Vastuvidya prathisthanam, Calicut
- “Geoinformatics”, PSG College, Coimbatore.

9. PUBLICATIONS:

Books Published (Language: Malayalam):

- Vellam (water), DC Books, Kottayam, India (2001)
- Kudivellam (drinking water), Rainbow Book Publishers, Chengannoor (2003)

Monographs (Language: Malayalam):

- Keralathile Nadikal (Rivers of Kerala)
- Indian Railway.
- Nanotechnology.

Journals:

Ajaya Kumar K, Tamil Selvan R, N A Siddiqui and Ashutosh Gautam, “Scope for Developing Accident Causation Model of Road Transportation of Hazardous Materials,” International Advanced Research Journal in Science, Engineering and Technology, Vol 2, Issue 10, October 2015.

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National Conferences:

Ajaya Kumar K, Asha Murali, The effect of Information and Communication Technology in reducing road accidents- A case study from Kerala- International Conference on Advanced Trends on Engineering and Technology (ICATET2014), Vimal Jyothi Engineering, Chemperi India (2014)

Ajaya Kumar K, Anuthaman S, SureshBabu D S, Quantification of Submarine Groundwater Discharge- A case study from South Kerala- National Conference on Emerging Trends in Engineering and Technology 2007 held at St. GITS College of Engineering, Kottayam. (2007)

Ajaya Kumar K, Traditional well construction materials- National conference of Architectural Engineers (NCArE), held at Regional Engineering College, Calicut. (1995)

Ajaya Kumar K, Ancient construction techniques- a bird's eye view, National conference of Architectural Engineers (NCArE), held at Regional Engineering College, Calicut. (1994)

Articles under review:

Ajaya Kumar K, N A Siddiqui , Kanchan D B and Ashutosh Gautam, Tolerability of risks in Road Transportation of Hazardous Materials, Safety Science. (submitted on 13.09.2016)

Ajaya Kumar K, N A Siddiqui , Kanchan D B and Ashutosh Gautam, Accident Causation Model for the Road transportation of Hazardous Materials, Accident Analysis and Prevention. (submitted on 11.10.2016)

10. SOFTWARE SKILLS:

- Operating System: DOS, Windows
- Languages known: C, FORTRAN, Pascal
- Word-processing: WordStar, WordPerfect, MS Word
- Page layout: PageMaker, Text maker
- Graphics: Adobe Photoshop, CorelDraw
- Drawing: AutoCAD
- Analysis & Design: ASAP, STAAD, SCADDS
- Planning: Primavera, MS Project
- Spreadsheet: MS Excel, Lotus 123, Surfer
- Database: MS Access
- GIS: Arc view, MapInfo
- Script: Arc Avenue
- Modeling& Simulation: ALOHA, PMWIN, Visual Modflow, MATLAB.

11. HONOURS/POSITIONS

- Secretary cum treasurer of ISTE, AJCE Chapter. (2008)
- Member, Editorial Committee, ICEM, Oman.(2008)
- Member, Academic Council, AJCE.(2007)
- Editor in charge of Newsletter of Indian Society for Technical Education, Kerala Section. (2000-2004)
- Editor in charge of Times Ads, the first advertisement only weekly in Malayalam. (1997-1999)