RISK MANAGEMENT STRATEGY FOR ROAD TRANSPORTATION OF LNG

A Thesis

by

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ABSTRACT

Liquefied natural gas is a fast growing source of clean energy in the U.S. This industry has been keeping an excellent safety record in the manufacturing, handling, transportation and distribution sectors. Even with the safety record, there have been a number of catastrophic incidents in the past as well as some incidents that did not lead to significant damage.

There have been a lot of studies on safety and risk management on LNG facilities and LNG marine transportation. But very few studies have been done on risk management of LNG road transportation. LNG is transported by road in certain areas in U.S. and safety assessments should be performed to ensure its safe transportation. This study investigates the hazards and risks associated with LNG transportation by focusing on road transportation. It analyses road transport incident history and identifies different scenarios leading to LNG road transport incidents. Hazard Identification was performed to list the hazards and their impact. The measures for reducing their risk are then evaluated qualitatively. For a complete overview of incident scenarios, a bow-tie analysis was performed. For the prevention and mitigation of LNG incident initiated by spill, a set of safety barriers are proposed. In the analysis it was found that, among the safety barriers a number of them lack proper standard and guidance. The barriers maintenance and inspection, traffic rule enforcement, road condition improvement, training and competence and un-ignited gas cloud mitigative control were found lacking

adequate guidance and therefore recommendations were provided for improving them. Based on the identification and assessment of incident scenarios and study of existing codes and standards, recommendations on risk management strategy are provided. In the assessment of scenarios in PHAST software, effects of thermal radiation and vapor concentrations of LNG were compared with the safety distances provided in different emergency response guidelines and their effectiveness were discussed.

DEDICATION

To my parents for all their love, encouragement and support.

To my husband for his endless love and constant support.

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I would like to thank my academic advisor, Dr. Sam Mannan, for his endless encouragement and support throughout my graduate study. He has helped me in some difficult situations and provided critical and creative suggestions. I would like to acknowledge my committee members, Dr. Mahmoud El-Halwagi and Dr. Ivan Damnjanovic. I am deeply grateful to my team leader Dr. Delphine Laboureur for her endless motivation, guidance and feedbacks. I would like to thank Dr. Pasman and Dr. Waldram for their expert advice and guidance in my research. I am grateful to my colleagues in Mary Kay O'Connor Process Safety Center for their help, advice and most of all great memories. I appreciate the staff, team leaders at the center specially Ms. Valerie Green for all the help and guidance.

I thank God for providing me with the ability, will and opportunity to complete this degree. Finally, thanks to my parents for their encouragement, and to my husband for his love and support.

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CHAPTER I

INTRODUCTION

1.1 Background

Natural gas is becoming significant as clean source of energy in United States. It is used in homes for heating and cooking, and by public institutions and industries for direct use or to generate electric power and as a fuel in natural gas powered vehicles. According to Annual Energy Outlook 2014 with projections from 2012 to 2040 published by U.S. Energy Information Administration, U.S. total natural gas consumption will raise from 25.6 trillion cubic feet (Tcf) in 2012 to 31.6 Tcf in 2040 [1]. Figure 1 shows U.S. natural gas consumption by sector projecting from 2012 to 2040. Although transportation sector accounts for a small percentage of total U.S. natural gas consumption according to the figure, natural gas use by heavy duty vehicles, trains and ships shows the largest percentage growth of any fuel in the projection [1].

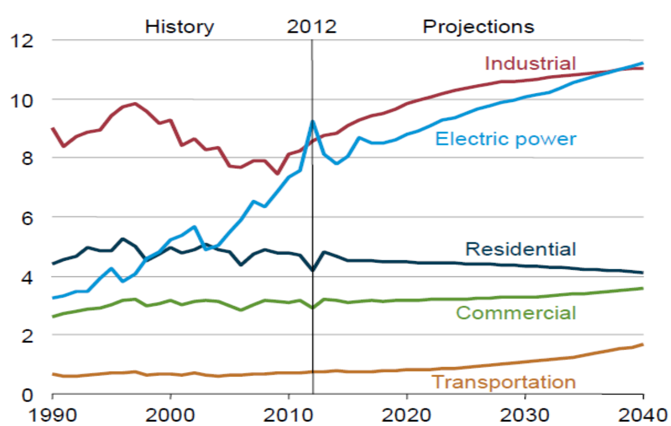

Figure 1: Natural gas consumption by sector, 1990-2040 (trillion cubic feet) [1]

Natural gas is liquefied to produce LNG (Liquefied natural gas) so that it can be easily and economically stored and transported. It is then transported from liquefaction facilities to receiving terminals and regasification facilities [2]. The LNG value chain is shown in figure 2. Although most of the LNG is transported by waterway, a significant amount of it is transported by tanker trucks on roadways which transport LNG from the receiving terminal to vehicle refueling stations.

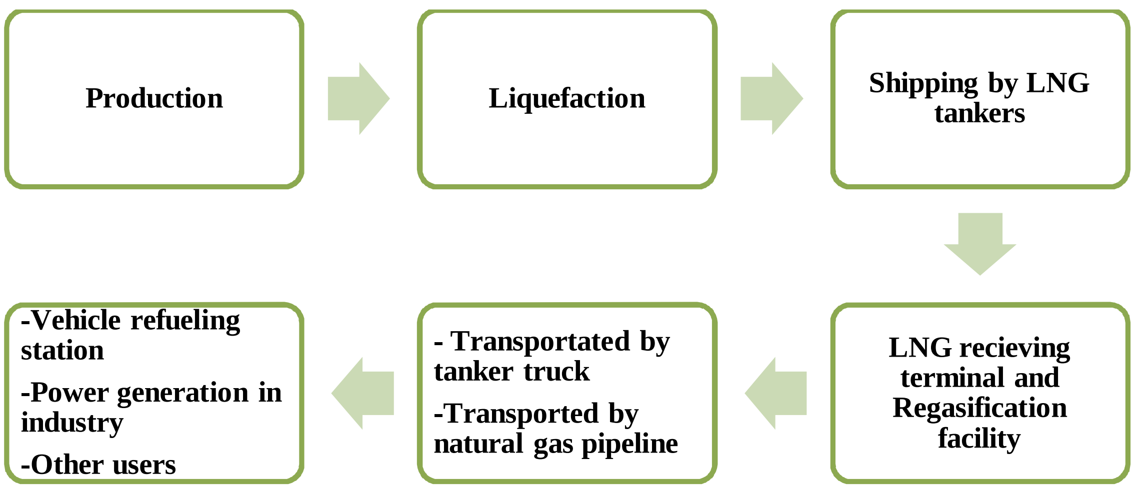

Figure 2: LNG value chain

For over four decades LNG has been transported and consumed worldwide and has been keeping an excellent safety record [3]. The reasons for this record are technical and operational evolvement, incorporation of the knowledge of risk and hazards associated with LNG into operations and strong application of standards and regulations to the LNG industry.

The demand for LNG is growing fast and it is expected to be more than double to approximately 480 million tons annually (MTA) over the next 20 years [2]. Several reasons for this future expectation are need for cleaner energy, abundant supply and relatively low price of LNG.

Although there were few major accidents associated with LNG, a lot of minor incidents and near misses also took place in LNG industry and transportation. A major portion of LNG is transported through waterways whereas a small percentage is transported by LNG truck tankers on roads. These truck tankers usually carry around 12,000 to 13,000 gallons of LNG [4]. Transportation of this large volume of LNG via highways and public roads raises many safety concerns. Also there are many LNG powered vehicles that also carry a significant amount of LNG and pose risks during transportation. With the forecasted increase in transportation of LNG and its use as a fuel could increase the probability of incidents. Therefore it is important to identify and assess the risks and hazards associated with LNG road transportation, and subsequent preventative and mitigative measures should be well organized and well-practiced.

This research looks to identify hazards and risks associated with road transportation of LNG by analyzing road transport incident history and identifying different scenarios leading to those incidents. For the prevention and mitigation of LNG incident resulting in a spill, a set of safety barriers will be proposed. Suggestion for risk management strategy will be provided based on the analysis, current regulations and guidelines.

1.2 LNG Properties

Natural gas is liquefied at -162 °C (-260 °F) under atmospheric pressure and this procedure reduces its volume by approximately 600 times. LNG contains mainly 95% methane and some other hydrocarbons such as ethane, propane, isobutene and may also contain small amounts of sulfur dioxide or carbon dioxide. LNG is non-toxic, odorless colorless, non-corrosive and weighs about 45% of water weight. Table 1 provides some important properties of LNG.

Table 1: Properties and flammability limits of LNG [3]

Flash point	-188^{0}C
Boiling Point	-160^{0}C
Lower flammability limit	15%
Upper flammability limit	5%
Auto-ignition temperature	540^{0}C
Stored pressure	Atmospheric
Vapor density at boiling point	1.82kg/m^3

LNG has a narrow flammability range (5%-15%) and has a very high auto-ignition temperature which makes LNG less likely to be ignited [3]. Moreover, storing in atmospheric pressure makes it flow and evaporate in case of a leak in the storage and there will be no immediate ignition. In a situation of an open LNG spill, it can burn only where the vapor might reach flammable condition [3]. Another hazard associated with

LNG is its cryogenic property. If LNG is released, direct contact with it can cause cryogenic burn.

1.3 Road Transportation of LNG

In the U.S. a number of companies operate LNG tanker trucks- Southeast LNG, LP Transportation, Tri-Mac, KAG.inc, Transgas, Clean Energy, J.B.Kelley [4]. LNG transportation system uses almost similar technology that is used to transport the other cryogenic liquids [4].

Figure 3: LNG tanker truck (http://www.thekag.com/)

Typical LNG tanker trucks are double-shelled insulated container. The approximate height of the trucks is 12’6” and lengths are 40 to 45 feet [5]. The sizes and lengths vary by manufacturers. The outer tank is made of carbon steel or stainless steel and the inner tank is usually made of stainless steel or high strength aluminum. The annular space between the two tanks contains insulating material such as perlite, fiberglass and foil backed paper (used by new trucks) and is placed under vacuum [5]. This insulation prevents heat transfer to the tank from the surrounding environment. This structural design and insulation system make the tank sturdy enough to act against impact, physical damage and fire.

For assessing safety of road transportation of LNG by tanker truck, identification of hazards and safeguards are necessary. The risks associated with LNG road transportation are high impact crashes or mechanical failure which might lead to injuries and property damage.

1.4 Objectives

The purpose of this study is to identify hazards and risks associated with transportation of LNG by truck tanker and provide suggestions on a risk management strategy for LNG road transportation. The objectives of this research are stated below:

- To perform a historical analysis based on the incident data for LNG road transportation
- To perform HAZID to find a list of hazards and evaluate the significance of the hazards and risk reducing measures qualitatively
- To perform a bow-tie analysis for a complete overview of major risks associated with LNG tanker truck transportation and to propose safety barriers to prevent and mitigate LNG spill from incidents.
- Identification and assessment of scenarios leading to LNG incidents
- To propose recommendation on risk management strategy for LNG road transportation based on current regulations and standards.

CHAPTER II

METHODOLOGY

2.1 Qualitative Risk Analysis for LNG Road Transportation

Risk management of LNG road transportation requires identification and evaluation of threats to potential hazardous events and analysis of the consequences and their severity. In this study a hazard identification technique, hazard review will be used to find and understand the significance of hazards associated with LNG road transportation. Then a bow-tie analysis will be performed to clearly visualize how a major hazardous event, LNG spill can occur and what safeguards can be used to prevent and mitigate them. The event tree in the bow-tie diagram provides list of threats to an LNG tanker truck leading to an LNG spill. For the prevention of LNG spill, a list of safety barriers will be provided by evaluating safeguards and safety gaps in existing standards and guidelines. Same methodology will be followed to identify mitigative safety barriers for the fault tree part in the bow-tie diagram where hazardous consequences from LNG spill would be listed.

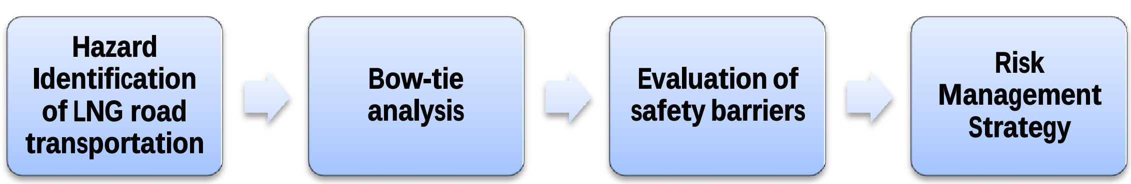

Figure 4: Methodology

2.2 Hazard Identification

Anything that has potential to cause harm to people, property and environment is defined as hazard [6]. A hazard can be a material, an activity or a situation. The process of identifying hazards is called Hazard identification (HAZID) [6]. This technique can be used to get a list of all hazards for their evaluation using risk assessment techniques and it is known as "failure case selection" [6]. HAZID can also be used to perform qualitative evaluation of the significance of hazards and risk reducing measures which is known as "Hazard Assessment" and will be used in this study [6].

There are many HAZID techniques available such as Hazard and Operability studies (HAZOP), What-if Checklist, Hazard review, Hazard Review, Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Failure Mode and Effect Analysis (FMEA) and so on. Among them hazard review technique will be used in this study to perform qualitative review of LNG road transportation for the identification of hazards and understand their significance. This method uses experience from different sources and is suitable for concept design. For the hazard review, the following concern will be addressed:

- Previous Safety Assessments
- Survey of previous accidents
- Previous experience
- Guidelines and code of practice
- Hazardous materials data

After identifying the hazards and their significance, a Bow-tie analysis will be performed to get a visual summary of incident scenarios and to propose a set of safety barriers.

2.3 Bow-tie Analysis

A bow-tie analysis is a structured approach for risk analysis. This analysis links potential threats and consequences in a single diagram [6]. The left side of a bow-tie is a simplified fault tree and the right side is a simplified event tree. For the better readability of the analysis the probabilities are not considered because the main function of a bow-tie diagram is to provide clear picture of mechanisms and to allow associated people to understand how a hazardous event can occur and what safeguards are available to prevent and mitigate them [6]. Therefore, the focus of the bow-tie analysis is on analyzing and proposing safety barriers and then incorporating them in the diagram. In this study, a set of safety barriers will be proposed for the prevention and mitigation of LNG spill from a truck tanker.

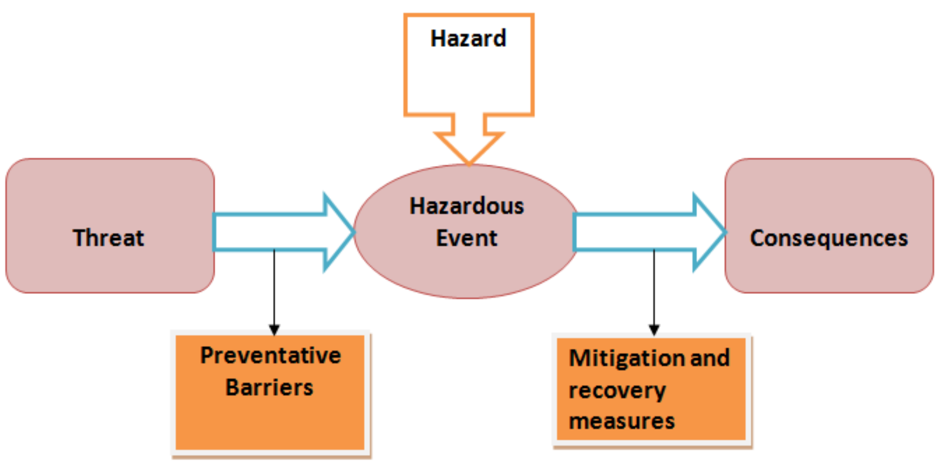

Figure 5: Bow-tie analysis

2.4 Safety Barriers

Sklet, S. defines safety barrier as physical and/or non-physical means planned to prevent, control or mitigate undesired events or accidents [7]. ISO: 13702(Requirements and guidelines for control and mitigation of fires and explosions on offshore production installations) defines prevention as means to reduce the likelihood of a hazardous event, control as means to limit the extent and/or duration of a hazardous event to prevent escalation and mitigation as means to reduce the effects of a hazardous event [8].

Before proposing safety barriers, barrier functions should be properly defined. Sklet, S. defines a barrier function as a function planned to prevent, control or mitigate undesired events or accidents [7]. In the bow-tie analysis for incidents in LNG transportation, two barrier functions were introduced-prevention and mitigation. In developing the barriers, a number of issues have been considered that are listed in table 2.

Table 2: Considerations to identify the safety barriers

Preventative barriers	Mitigative barriers
Prevent the hazard from being released	Minimize the effect
Keeping control	Limit the severity of the event
	Make sure controls do not fail

The barrier system was classified according to the barrier functions, based on the classification system recommended by Sklet, S. [7]. As shown in figure 6, barrier system can be classified as passive and active barrier system. This classification was also proposed by CCPS and Kjellen [9][10]. According to CCPS passive protection layer does not need to take an action for achieving its function to reduce risk and an active protection layer is required to be moved to different states in response to a significant change in a process condition [9]. Kjellen describes passive barriers as fixed in the design and active barriers as dependant on actions to function as intended [10].

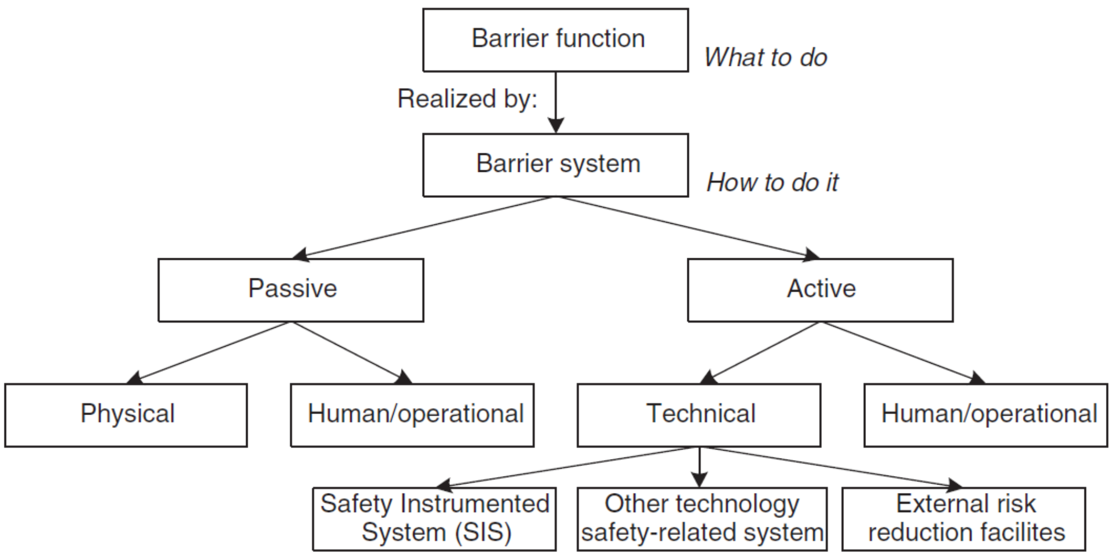

Figure 6: Classification of safety barrier system [7]

Passive barrier systems often are combination of physical and human/operational elements whereas active barrier system comprises of technical and human/operational elements. Sklet, S. adopted the 4th level classification in figure 5 from Hale [11] and classification of active technical barriers from IEC: 61511 [12].

After classifying the safety barriers for LNG road transportation according to Sklet, S., the barriers will be evaluated based on current regulations and standards. Then suggestions on risk management strategy for LNG road transportation will be proposed.

CHAPTER III

ANALYSIS

3.1 Hazard Review

Hazard review is a qualitative review of a system to identify hazards and to gain qualitative understanding for their significance [6]. For the hazard review, the following issues were addressed: previous safety assessment, survey of previous accidents, previous experience, guidelines and codes of practice, and hazardous materials data. This section provides more details on each of the steps, as applied to the hazard identification of road transportation of LNG.

3.1.1 Previous Safety Assessments

In this assessment, a study of previous risk assessments was done to obtain an outline appreciation of hazards. In a study of characteristics and prevention of road transport LNG accidents, the causes of LNG transportation accidents were analyzed [13]. These causes are fatigue driving, overloading, hazardous characteristics of LNG, absence of rigorous accident prevention and emergency measures, long distance transport, and unreasonable road design.

This study provided several recommendations to improve road transport condition for LNG such as requirements for vehicle type and safety, requirements of employees, requirements of roads and natural condition consideration. Figure 7 provides the LNG accident prevention strategy provided by the study:

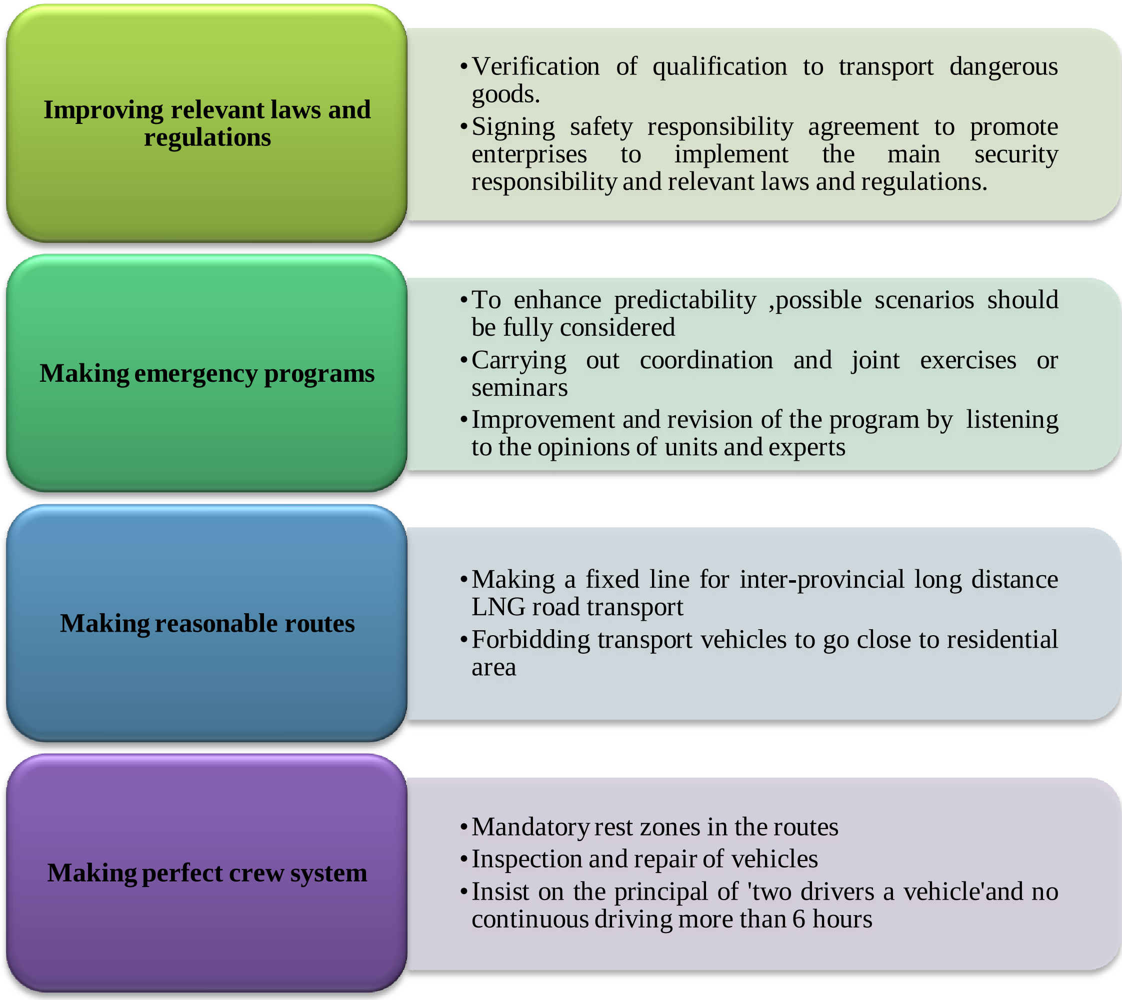

Figure 7: LNG transport accidents prevention, modified from [13]

In an analysis of the explosion of an LNG tanker truck containing liquefied natural gas [14] an attempt was made to clarify how and why it occurred. A historical analysis was made based on the statistics of accidents involving hazardous materials (total 12,179 accidents) and explosion consequence modeling was done. According to the historical study, 8.6% of the accidents occurred during road transport and only 9 of them involved LNG [14]. The incident mentioned earlier happened because the tanker turned over due to speeding on a downhill section of the road. Several causes for the accident were detected such as release of truck fuel, leakage of LNG from the safety valve and truck structure distortion.

The Idaho National Engineering Laboratory published a report in 1998 for LNG vehicle refueling stations [15] which included qualitative assessment of worker and public risk associated with tanker truck deliveries and end use vehicle fueling. For this analysis, Master Logic Diagram, a FMEA (Failure mode and effect analysis) and historical operating experiences were used to identify accident initiating events. In their analysis a number of initiating events to LNG release was identified that are listed in the Master logic diagram in Figure 8 that they developed. Although these initiating events were related to LNG vehicle refueling station, some would be applicable for LNG tanker trucks.

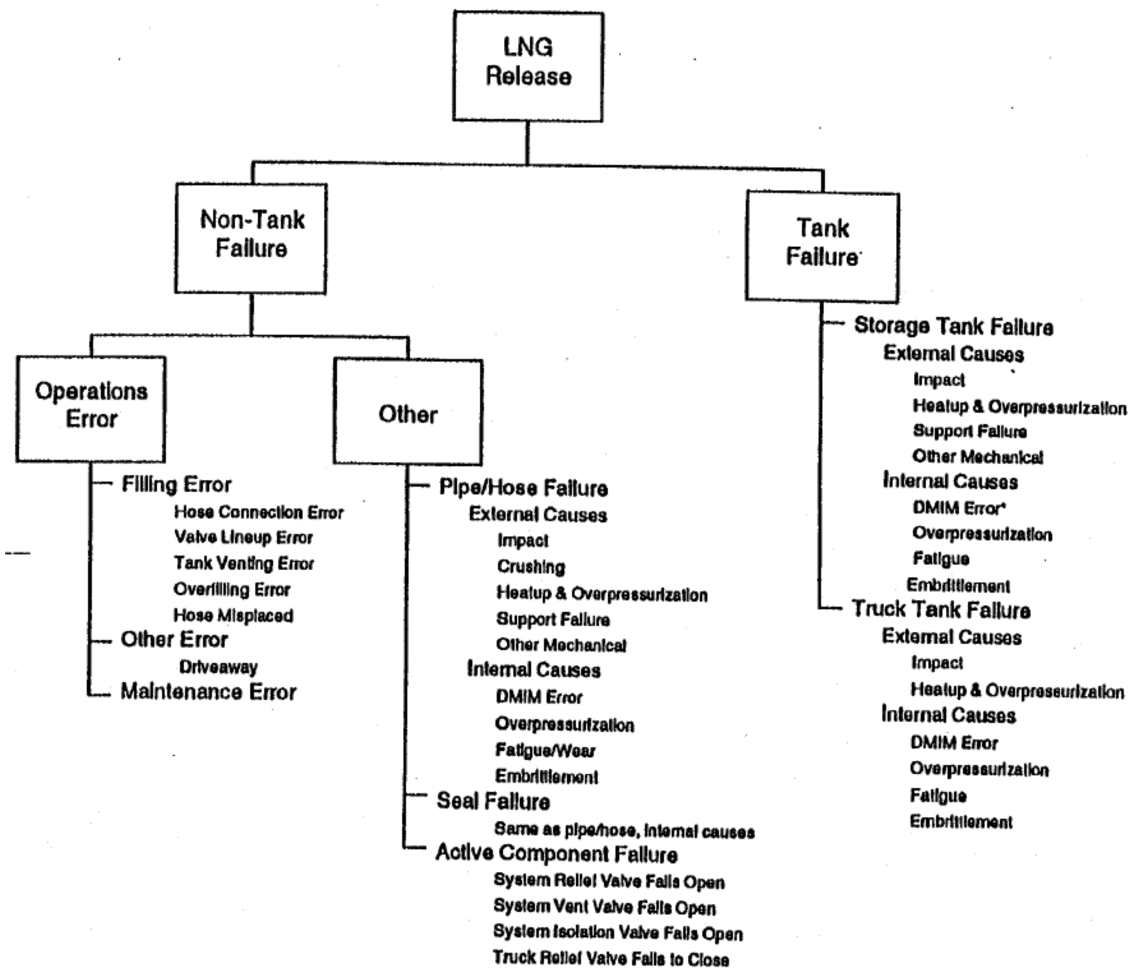

Figure 8: Master logic diagram: LNG release

3.1.2 Survey of Previous Incidents

In this study, a database has been developed with a collection of LNG tanker truck incidents. Although the process cannot be comprehensive, it will ensure previous accidents are not overlooked. The data in Appendix A was taken from the Pipeline and Hazardous Materials Safety Administration incident report database and other relevant papers [16][17]. All of these incidents involved LNG truck tanker from different companies in U.S. From the database, risks in road transportation were identified. Appendix A lists LNG road transportation incidents from 1971 to 2012.

The data was collected to find out the possible causes of LNG road transport accidents and percentage contribution to LNG transportation accidents is shown in figure 9. 23% of the accidents were caused by mechanical failure such as a loose or cracked valve. Rollover incidents were 26% of the total accidents. 26% percent accidents were caused by human error such as driver inattentiveness, speeding, drunk driving and ignoring traffic rules. Blowout (punctured tire) and other factors such as sliding down the road, wheel problem and so on contributed to the accidents by 3% and 5% respectively.

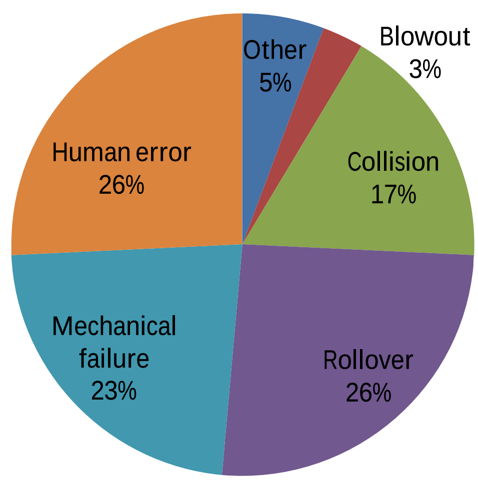

Figure 9: Percentage contribution to LNG road transportation accident

3.1.3 Previous Experience

In this study near miss accidents and operating problems associated with LNG tanker trucks and other LNG vehicles have been assessed. Detailed report on the incidents [16] presented by the authorized persons of the companies were analyzed which provided a picture of the seriousness of the incidents. Most of the incidents found in history (Appendix A) are near miss incidents associated with LNG tanker trucks. Because of the hazardous properties of LNG, (*i.e.* cryogenic, flammable, asphyxiant), any transportation system is prone to incidents no matter how safe the system is. Although there have not been many serious incidents, lots of near misses were found in the analysis. The more we know about the leading causes of near misses, the lower the risk. So near misses should be accounted to prevent any future incidents.

3.1.4 Hazardous Materials Data

Analysis on hazards of LNG was done based on the Safety Datasheets found from different companies. Based on the composition of their LNG, the hazard ratings are different for them.

Table 3: Chemical composition of LNG from different companies [18][19][20][21][22]

Company	**Chemical composition**	**Hazard Rating**
FortisBC	Methane (95%), Ethane (3%), Propane (1%), Nitrogen (1%)	NFPA Rating: Health 2 Flammability 4 stability 0
NW Natural	Methane (>93.5%), Ethane (3.8%), Propane (1%), i-butane (<0.1%), n-Butane (<0.1%), i-Pentane(<0.1%), n-Pentane(<0.1%), n-Hexane(<0.1%), Carbon Dioxide(0.3%), Nitrogen(1.2%), t-Butyl Mercaptan(<30 ppm), Methyl Ethyl Sulfide(<3 ppm), Hydrogen Sulfide(<5ppm)	NFPA Rating: Health 3 Flammability 4 stability 0
Linde	Methane (62-93%), Ethane (3-11%), Nitrogen (1-9%), Propane (1-7%), N-Butane (1-3%), Isobutane (1-3%), Helium (<2%), Isopentane (<1%), pentane (<1%), Carbon Dioxide (<1%)	NFPA Rating: Health 3 Flammability 4 stability 0
EP Energy	Methane (60-95%), Ethane (1-60%), Propane (20-60%), i-butane (0-4%), i-pentane (0-2%), i-Hexane (0-2%), n-Butane (2-5%), n-Pentane(5-25%), n-Hexane(<2-13%), Carbon Dioxide(0-5%), Nitrogen(0-15%), Hydrogen Sulfide(varies)	NFPA Rating: Health 2 Flammability 4 stability 0
ConocoPhillips	Methane (100%)	NFPA rating: Health 3, Flammability 4, stability 0

Although the hazard class is different, hazardous properties are common for LNG from different sources..

Common hazards of LNG are listed below:

- Flammability
- Pooling and brittle failure
- Phase change and overpressure
    - -Vessel overpressure failure
    - -Boiling Liquid Expanding Vapor Explosion (BLEVE)
    - -Rapid Phase Transition (RPT)
    - -Vapor Cloud Explosion
- Cryogenic Burns
- Environmental Effects

3.1.5 Guidelines and Code of Practice

There are several standards that LNG industry must comply with but there are not enough guidelines specifically for LNG road transportation.

- LNG industry must comply with air and water standards established by U.S. Environmental Protection Agency and state environmental agencies [23]. These standards were designed to protect public health and welfare from different types of pollutants by enforcing vehicles to use state-of-the-art emission control technologies and plants and facilities to use modern pollution control technology.
- NFPA 59A-Standard for the Production, Storage and Handling of Liquefied Natural Gas was the first LNG standard released by the National Fire Protection Association (NFPA). It states some standards on training of all personnel involved with LNG and standards applied to tank vehicle and tank car loading

and unloading facilities [24]. This standard states some tank vehicles not under the jurisdiction of DOT (U.S. Department of Transportation) shall comply with CGA341- the Standard for Insulated Cargo tank Specification for Cryogenic Liquid, and Flammable liquid tank vehicles shall comply with NFPA 385 (the standard for tank vehicles for flammable and combustible liquids) [24].

- NFPA 57-Liquefied Natural Gas (LNG) Vehicular Fuel Systems Code applies to the design, installation, operation, and maintenance of LNG engine fuel systems on all types of vehicles. This standard is also applicable to their associated fueling (dispensing) facilities [25].
- NFPA 52 provides standards to mitigate fire and explosion hazards associated with compressed natural gas (CNG) and liquefied natural gas (LNG) engine fuel systems and fueling facilities [26].
- LNG tank trucks must comply with design standards provided by Department of Transportation, ASME and some others which are provided below in table 4.

Table 4: Standards for LNG tank truck construction [27][28][29][30][31]

Tank construction	DOT CFR49 specifications– 49 CFR parts 173.318 and 178.338 (MC-338) DOT-4L ASME Section 8 Div 1 NFPA 52 SAE J2343
Material	ASTM Standard B 580 DOT-4L

In some regions of the U.S., safety concerns regarding LNG manufacturing, handling, storing and transportation led to the implementation of laws and regulations. For example, in New York City there was a moratorium on the siting of LNG facilities and intrastate transportation routes which existed from 1973 to 1999 [4]

The standards listed above provide a guideline for operating a safe LNG plant and road transport. They do not specify the hazards that each measure is intended to control. But it can be checked if road transportation of LNG tanker truck conforms to good engineering practice.

3.2 Bow-tie Analysis

The potential threats leading to LNG spill were detected from the hazard review technique that has been done and are listed in table 5.

Table 5: Potential threats for LNG spill from truck tank

Threats	Reason
Mechanical Failure	Loose valve cracked valve piping failure
Structural failure	Brittle fracture Corrosion Loss in tank integrity
Impact	Vehicular crash Terrorist attack
External fire	Fire initiated by truck fuel Fire initiated by other source
Rollover	Operation problem Poor road condition
Human error	Driver fatigue Ignoring traffic rules

The potential consequences of an LNG spill are listed on the right side of the bow-tie diagram. Figure 10 shows a simple version of the bow-tie diagram where the threats and consequences are listed. For the risk management a set of safety barriers are proposed to prevent threats causing any hazardous event and also to recover after an incident.

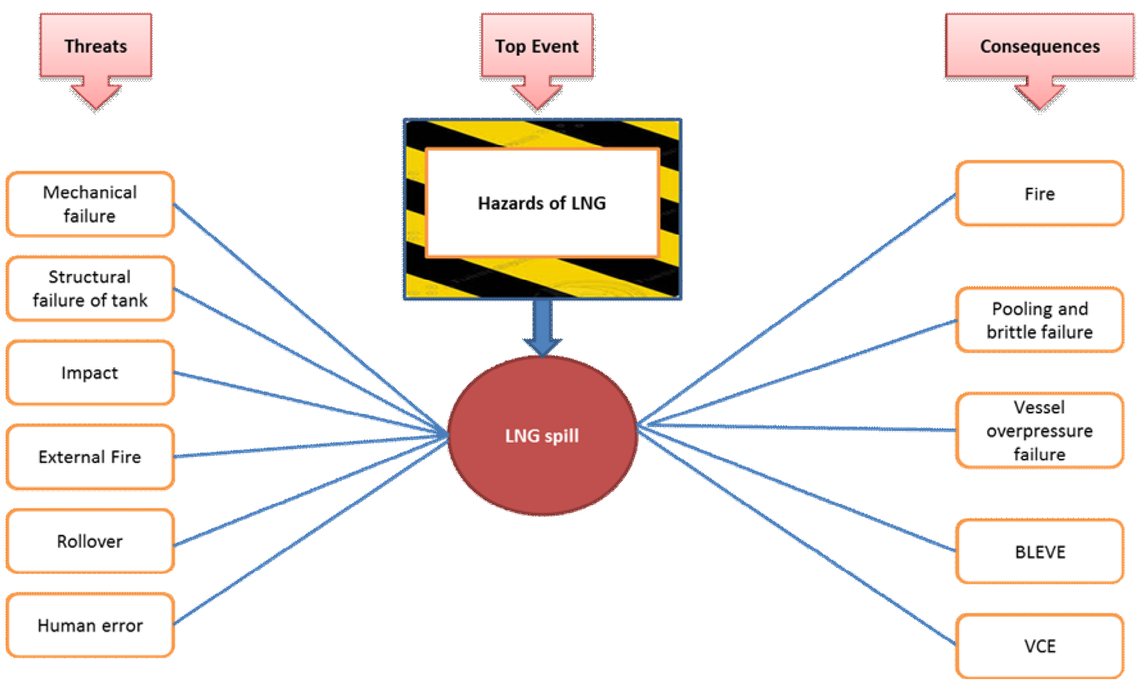

Figure 10: Bow-tie analysis for LNG spill from LNG tanker truck

According to the classification, the safety barriers required for the prevention and mitigation of LNG spill after an LNG tanker truck accident are listed in table 6.

Table 6: Safety barriers for prevention and mitigation of LNG spill from LNG tanker truck incident

Barriers	Characterization	Prevention	Mitigation
Passive, physical	-Functioning continuously -Might be temporary	• Structural design • Material selection • Pressure and temperature design • Passive fire protection	• Structural design • Passive fire protection • Congestion reduction
Passive, human/operational	-Functioning continuously -Implemented as part of high risk activity -Executed by human with the support of an organization	• Training and competence • Improved road condition • Traffic rule enforcement • Certification of LNG truck tank • Driver proficiency	• Training and competence
Active, technical	-Functions when needed -Includes technical tools	• Active fire protection system • Maintenance and inspection	• Un-ignited gas cloud mitigative control • Active fire protection system
Active, Human/operational	-Continuous/activated on demand -Integrated part of work process to reveal potential failure	• Emergency procedure	• Emergency procedure

3.2.1 Preventative Safety Barriers

Preventative barriers are provided to work before an initiating event takes place. They ensure that the accident does not happen or at least decelerate the development of the initiating event leading to an accident. As mentioned earlier, from the historical analysis of LNG tanker truck incidents a number of threats were identified that might lead to LNG spill and are listed in table 5. Based on the root causes of these threats, preventative barriers were proposed in different classes of the barrier system. Figure 11 shows a representation of the classification of the preventative barriers and figure 12 shows their placement in the bow-tie analysis.

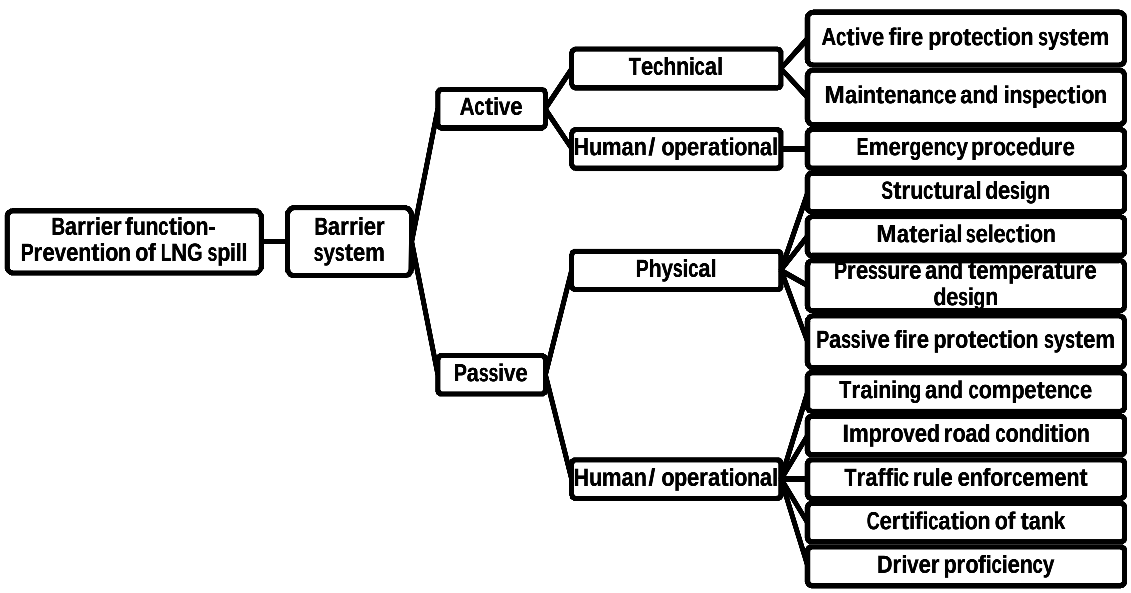

Figure 11: Classification of preventative safety barriers

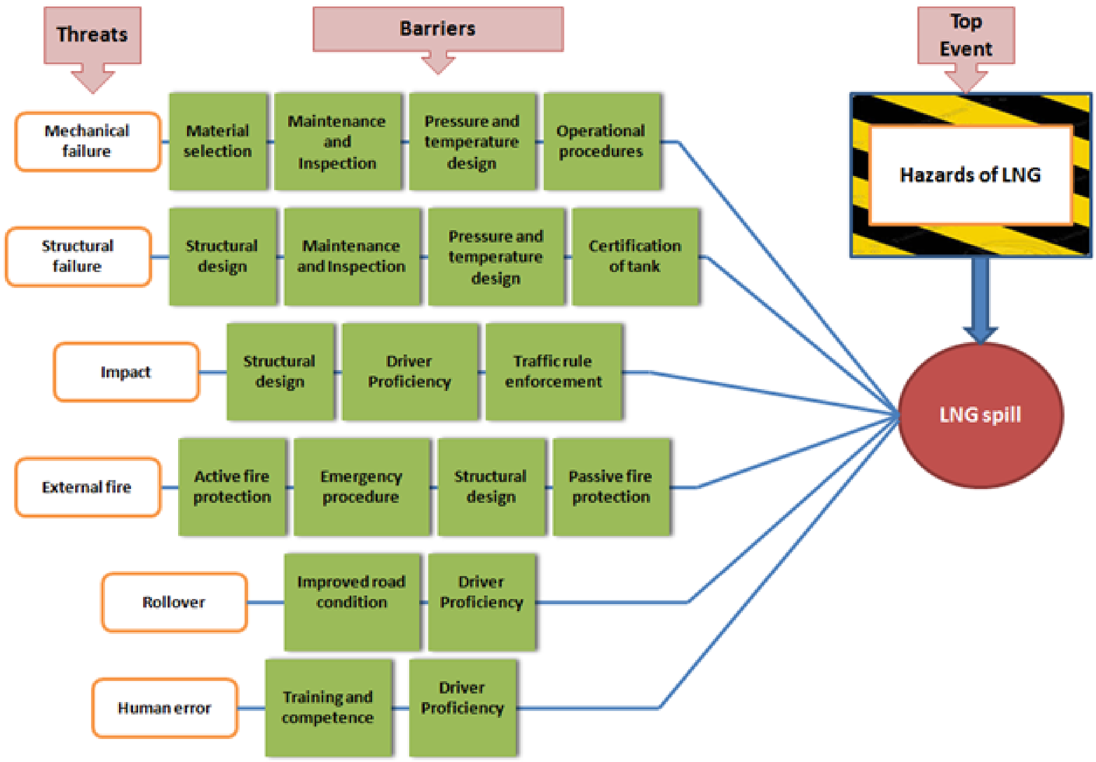

Figure 12: Preventative barriers for LNG spill in the bow-tie analysis

3.2.2 Mitigative Safety Barriers

Mitigative barriers work after specific initiating event has happened. They are supposed to protect people, environment and property from the consequences of the event [7]. After an LNG spill has taken place, there are a number of consequences that can occur such as fire, pooling and brittle failure, vessel overpressure failure, BLEVE, vapor cloud explosion. Rapid phase transition is one of the consequences that can happen in the presence of water but for a scenario in road, it can be eliminated. Figure 13 shows a representation of the classification of the mitigative barriers and figure 14 shows their placement in the bow-tie analysis.

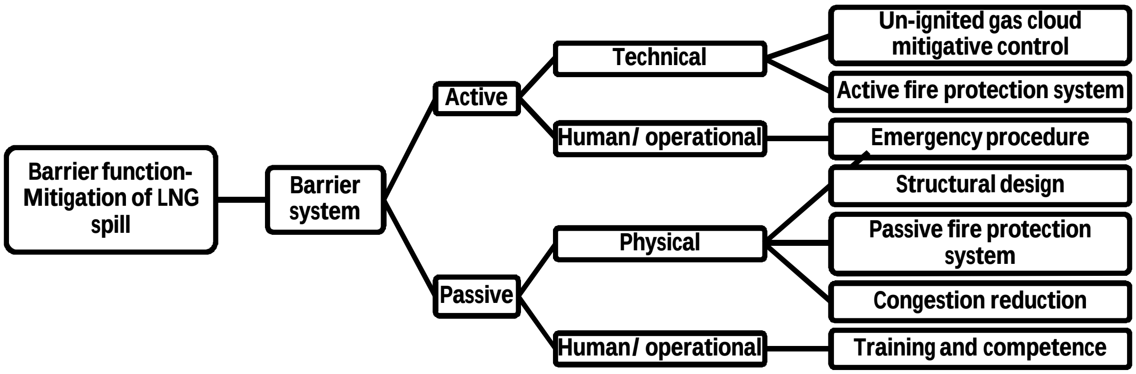

Figure 13: Classification of mitigative safety barriers

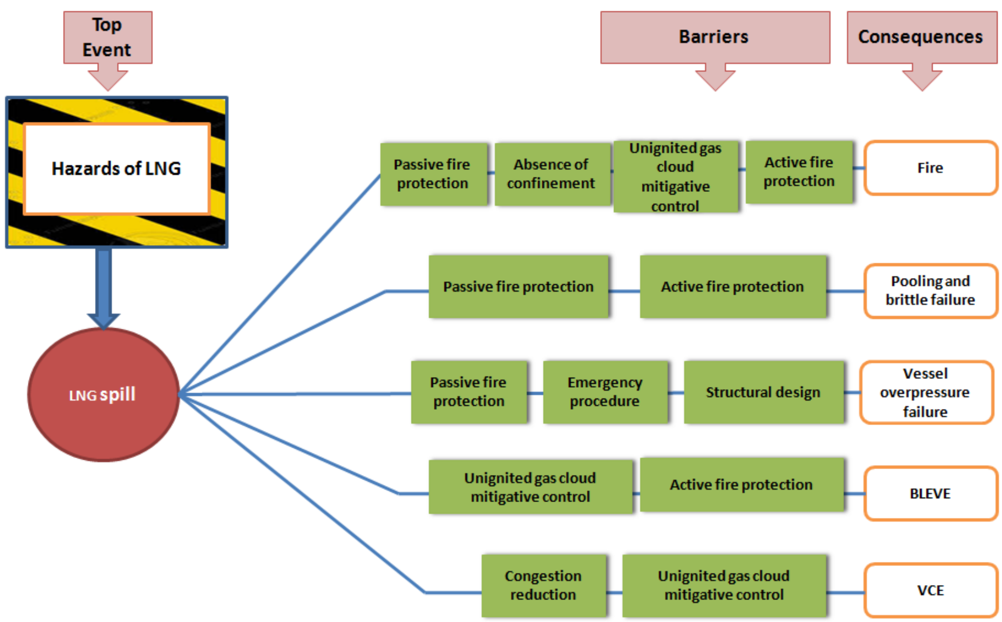

Figure 14: Mitigative barriers for LNG spill in the bow-tie analysis

3.3 Risk Management with Safety Barriers

3.3.1 Structural Design and Material Selection

The material to be used for LNG truck trailers should provide enough strength to avoid any leak and stay intact during a crash and should be able to withstand very low temperature to avoid brittle fracture. The tanks are generally made of stainless steel or aluminum (inner part) and carbon steel (outer part) [4]. Another concern in material selection is avoiding corrosion.

Several standards have been found for safe structural design of LNG truck trailers and if the standards are properly followed risk of a structural failure can be greatly reduced. U.S. and Canadian tank construction standards (DOT-4L, ASME Section 8 Div 1, NFPA 52 and SAE J2343) are followed for the construction of the double walled vacuum insulated tanks [26][28][29][30]. The LNG trailers built in the US comply with the Department of Transportation's design standards DOT CFR49 specifications– 49 CFR parts 173.318 and 178.338 (MC-338) [27]. The tanks are double walled and insulated, robustly designed to avoid any physical or fire damage. [4] Specifications of several features that may or may not be installed are provided in the DOT standard such as:

- The temperature of the cryogenic liquid should not be colder than the design temperature. [27]
- The jacket of the insulation of the tank should be made of steel if a vessel is used to transport the cryogenic liquid. [27]

- The material loaded in the tank should not be able to combine chemically with any residue in the packaging. [27]
- Any valve or fitting made of aluminum outside the jacket that retains lading during transportation should not be installed in the tank used to transport cryogenic liquid. [27]
- Any valve or fitting made of aluminum that has the possibility to come in contact with oxygen in the cryogenic liquid form should not be installed in the tank unless the parts are anodized in accordance with ASTM Standard B 58. [27]
- The cargo tank should be provided with a manhole if it carries oxygen or any other cryogenic liquid. [27]

3.3.2 Maintenance and Inspection

Maintenance, inspection and repair of truck trailers are essential for safe transportation of LNG. Current safety regulations promulgated by Federal motor carrier safety administration (FMCSA) cover all aspects of vehicle operation and maintenance requirements in 49 CFR part 396.49 CFR part 396.3 provides detailed instruction for inspection, repair and maintenance of all general motor carrier [32]. This standard specifies requirements on inspecting frame and frame assemblies, suspension systems, axles and attaching parts, wheels and rims and steering systems [32]. It also requires recordkeeping of inspections, tests, repairs and maintenance. The standard also provides specification on forbidding unsafe operation.

Although 40 CFR part 393 provides requirements applicable to compressed natural gas fuel containers, it does not provide any requirements for LNG fuel containers or LNG tanker trucks [33]. Since LNG is a cryogenic liquid, requirement of appropriate fuel tank tests should be standardized and applied. Different companies might have different procedures but proper regulations are required to enforce maintenance and inspection.

3.3.3 Pressure and Temperature Design

LNG tanker trucks are equipped with pressure relief devices to prevent overpressure. The LNG tanks usually have a design pressure of 100 psig and normally operate at less than 70 psig. In case of exceeding the pressure level, the safety release valve opens to release the gas safely to the atmosphere. There are also secondary relief devices available which are provided with a higher pressure limit. These equipments should be properly designed and installed. There are specifications for designing of pressure relief systems which are controlled by CGA S-1.2-1980 (pressure relief device standards part 2-Cargo and portable tanks for compressed gases). [34]

Table 7: Regulation for pressure relief system [34]

Pressure relief systems and pressure control valves	Tanks must be protected by: • A primary system of one or more pressure relief valves. The primary pressure relieve system must have a total flow capacity at a pressure not exceeding 120 percent of the tank's design pressure. • A secondary system of one of more frangible discs or pressure relief valves. The secondary pressure relief system must have a total flow capacity at a pressure not exceeding 150 percent of the tank's design pressure.
Additional	• A cargo tank may be equipped with optional pressure control valves set at a pressure below tank's design pressure • One or more frangible discs set to function at a pressure not less than one and one-half times or more than two times the tank's design pressure.

For liquefied compressed gases in un-insulated containers and in insulated containers, the minimum required flow capacity of the pressure relief device(s) shall be calculated using the formula [34]

Q_a=$G_uA^{0.82}$

Where

U = Total thermal conductance of the container insulating material Btu/ (hr.ft^2.F) when saturated with gaseous lading or air at atmospheric pressure, whichever is greater.

U=(Thermal conductivity of insulation/Thickness of insulation)

Q_a = Flow capacity in cubic feet per minute of free air

G_u = Gas factor for un-insulated container

A = Total outside surface area of the container in square feet

The standard above can be used for compressed natural gas. For liquefied natural gas there are several standards in UK that can be used to design valves for cryogenic systems. For designing valves for cryogenic system several considerations should be taken into account such as thermal expansion and contraction in cryogenic temperature, providing tight shut-off without leakage, deciding whether to fit flanged or welded valves, possibility of ‘plugging’ due to ice or hydrate formation and so on[35].

Valves selected to be used in LNG service should be checked if it is designed and manufactured to relevant standards and codes. Table 8 shows general design features specific to cryogenic requirements.

Table 8: General design features specific to cryogenic requirements [35]

ELEMENT		DESIGN FEATURES
Stem sealing device. (Gland packing at the top of the extension)		Consider the wear characteristics of the packing material and the surface smoothness of the valve stem. Consider the potential vapour leakage from the stem in terms of ISO 14000 requirements.
Bonnet Joints Attaching the valve cover to valve body		To meet BS EN 12567:2000 (4.3). The valve shall be designed to take into account the thermal stresses in transient state occurring during cool down and warm up operation.
Actuating thread		Consider potential seizure due to materials used. Anti-galling austenitic stainless steel prevents seizure and valve failure.
Anti-blowout stem/shaft/spindle retention. This applies to all valves with stem/shaft/ spindle protruding into the pressure area.		To meet BS EN 12567:2000 (5.11). Each valve stem/shaft/spindle shall be fitted with an anti-blow out feature for maximum safety. Serious injury can occur if the stem could be ejected with force when the valve is opened.
LNG liquid lock in the stem/shaft/spindle area when the valve is in the full open position		To meet BS EN 12567:2000 (4.4). To ensure liquid is not trapped in bonnet extension or any other cavity of the valve arrangement. A safety device must be fitted to any area where liquid lock can occur to prevent over pressurisation. The device must not release cargo to atmosphere.
Obturator/Disc/wPlug. The mechanism to seal the valve		The design must take vibration into account, especially for marine applications. A vibration-proof connection between stem and plug should allow sealing faces to remain stationary during final closing to prevent galling, wear and seat damage.
Flow Path		The bore should be selected taking account of pressure drop across the valve
Cryogenic Valve Automation		The valve must be installed so it is able to support the weight of the actuator in all conditions including marine applications (where vibration is significant). This is to prevent failure due to excessive stresses from the weight of the actuator. It may be necessary to fit local supports and to strengthen the pipeline in way of the valve, especially in branch locations

There are also some tests that are specifically required for cryogenic valves:

- Cryogenic prototype test B S 6364: 1984 [35]
- Cryogenic production test BS6364:1984 (offers guidance and direction on what to look for to ensure that the test is carried out correctly) [35]

3.3.4 Certification of Truck Tanks

According to NFPA-57, Code for Liquefied Natural Gas Vehicular Fuel Tanks & Fueling Facilities, 2002 Edition, LNG fuel tanks are required to be designed, fabricated, tested and marked in accordance with the requirements of DOT Specification 4 L [25]. Also ASME boiler and pressure vessel code- Rules for the Construction of Unfired Pressure Vessels is also another code that can be followed [29]. DOT specification 4-L, section 173.316 and 173.18 also provides manufacturers the requirements for "cryogenic liquids in cylinders" & "cargo cryogenic containers" [36]. There was no specification found for the certification testing found for LNG truck trailers.

3.3.5 Driver Proficiency

A lot of incidents with LNG truck trailers were caused by improper driving, poor judgment, fatigue driving. Drivers should be properly informed about the hazardous materials and their driving proficiency should be certified and maintained. For someone to obtain a Commercial Driver license with a hazardous materials endorsement (HME), he must go through a security threat assessment and obtain clearance from the federal Transportation Security Administration (TSA) [37]. In some places drivers are required to pass a HAZMAT knowledge test. But there are no global HAZMAT driver training provided by the authority. HAZMAT employers determine the adequacy of training and provide them accordingly. Federal regulation requires a person operating a HAZMAT vehicle be trained according to the requirements of 49 CFR parts 390 through 397 [39]. These regulations specify requirements related to:

- Qualification of drivers and driving instructors

- Parts and accessories necessary for safe operation
- Driving of commercial motor vehicles
- Hours of service of drivers
- Transportation of hazardous materials; driving and parking rules
- Inspection, repair and maintenance

Drivers operating a cargo tank or portable tank with a capacity of 1,000 gallons or more must receive training applicable to the requirements and have the appropriate State-issued commercial driver's license required by 49 CFR part 383 [38]. If these regulations are properly followed and drivers are well trained, incidents can be reduced significantly.

3.3.6 Traffic Rule Enforcement

To decrease number of incidents, enforcement of some traffic rules are important, such as, timing of transportation to avoid busy periods in urban areas. Also identification of specific risk areas such as congested areas, proximity to water currents, communities, poor conditioned roads, heavy traffic areas, areas with scarce visibility should be enforced by the regulatory agencies. Restrictions on hours of driving, speed control, enforcement on using Taco-graphs can make the road transportation of LNG much safer. US federal regulation 49 CFR part 395 provides requirement of hours of service and break for drivers. According to the rule a specially trained driver who operates a commercial motor vehicle specially constructed to service natural gas or oil wells that is equipped with a sleeper berth may take 10 consecutive hours of off-duty time and no rest period can be shorter than 2 hours.

There are rules for drivers in UK regarding driving breaks, driving limits, daily and weekly driving limits and so on. The following table summarizes EU rules for driving hours. Adoption of these rules their enforcement can reduce the risks in LNG road transportation.

Table 9: EU rules for driving hour

Breaks from driving	A break of no less than 45 minutes must be taken after no more than 4.5 hours of driving. The break can be divided into two periods – the first at least 15 minutes long and the second at least 30 minutes – taken over the 4.5 hours.
Daily driving	Maximum of 9 hours, extendable to 10 hours no more than twice a week.
Weekly driving	Maximum of 56 hours.
Two-weekly driving	Maximum of 90 hours in any two-week period.
Daily rest	Minimum of 11 hours, which can be reduced to a minimum of 9 hours no more than three times between weekly rests. May be taken in two periods, the first at least 3 hours long and the second at least 9 hours long. The rest must be completed within 24 hours of the end of the last daily or weekly rest period.
Multi-manning daily rest	A 9-hour daily rest must be taken within a period of 30 hours that starts from the end of the last daily or weekly rest period. For the first hour of multi-manning, the presence of another driver is optional, but for the remaining time it is compulsory.
Ferry/train daily rest	A regular daily rest period (of at least 11 hours) may be interrupted no more than twice by other activities of not more than 1 hour's duration in total, provided that the driver is accompanying a vehicle that is travelling by ferry or train and has access to a bunk or couchette.
Weekly rest	A regular weekly rest of at least 45 hours, or a reduced weekly rest of at least 24 hours, must be started no later than the end of six consecutive 24-hour periods from the end of the last weekly rest. In any two consecutive weeks a driver must have at least two weekly rests – one of which must be at least 45 hours long. A weekly rest that falls across two weeks may be counted in either week but not in both. Any reductions must be compensated in one block by an equivalent rest added to another rest period of at least 9 hours before the end of the third week following the week in question.

3.3.7 Active and Passive Fire Protection

Active fire protection system might not be available instantly in case of a road accident but detection and alarm system can be installed for fast communication which would work as preventative barrier. Active fire protection systems as mitigative barriers applicable to LNG incident are [42]:

- Water curtains to contain/dilute/divert vapor cloud
- Portable gas drift detection system to ignition source or confined areas where a vapor cloud explosion is possible
- Cooling any nearby property, tanker or equipments
- Use of high expansion foam for vapor reduction
- Water monitor to offer limited dilution

Passive fire protection can help prevent incidents.

- Flame retardant materials
- Emergency shutdown system

NFPA 59A Standard for production, storage & handling of liquefied natural gas is used for general plant considerations, process systems, LNG storage containers, vaporization facilities, piping systems and components, instrumentation and electrical services, transfer of NG and refrigerants, fire Protection, safety and security [24]. There is no specific fire protection system for LNG truck trailers but the codes for fire protection, safety and security are applicable there.

3.3.8 Emergency Procedure

LNG truck trailers are provided with an Emergency Shutdown System which can be activated by the driver or automatically if a leak is detected by the system [43]. After activated, it closes the main liquid supply valve and stops the transfer pump. The vacuum insulated double walled tanks with insulation are designed to stay in place in case of an external fire [43].

According to an instructional procedure from Swedish Gas Association for emergency situation in LNG road transportation, there are different scenarios on which the emergency responders have to act on [44]. Instructions on the actions taken during an incident are clearly provided there.

-Evacuate certain area as described in table 10.

-Stop all engines and remove ignition source, other vehicles containing hazardous cargo

-Check any damage or leak; take liquid level and pressure readings

-Calculate gas concentration and emission area and modify evacuation radius accordingly

- Check if the leak can be stopped by shutting of the supply

-Since gas can be carried away in the direction of wind and find an ignition source, authorized personnel should take care of that.

-According to the condition of the vehicle, determine if it should be driven to a safe location, towed or emptied.

Table 10: Evacuation radius for different scenarios of LNG tanker truck accident [44]

Scenario	Evacuation radius	Additional tasks for the scenario
The truck has rolled over, standing upright, judged to be sound	100 m	Determine if the unit can be recovered without any special measure
Leaking gas with no fire	100 m	Spray water to the gas cloud to control and dissipate it
Leaking liquid with no fire	300 m	Stop spraying on the leak, if methane gas ignites
Leaking with fire	300 m	If the fire cannot be extinguished, allow the gas to burn while the tank is cooled
External fire effecting the unit	300 m	Move the transport away from the source of fire and if not possible cool the vehicles with water

3.3.9 Training and Competence

The driver of the LNG tanker truck and emergency responders should have adequate training to handle any emergency situation. Knowledge on safety data sheet and proper awareness of the hazards associated with LNG are required for a driver to be competent to drive the truck tanker. As stated earlier, Federal regulation requires a person operating a HAZMAT vehicle be trained according to the requirements of 49 CFR parts 390 through 397 [39]. Drivers operating a cargo tank or portable tank with a capacity of 1,000 gallons or more must receive training applicable to the requirements and have the appropriate State-issued commercial driver's license required by 49 CFR part 383 [38].

In the Texas A&M University, firefighters can be trained in handling LNG fire at TEEX Brayton Fire Training Field. There are other training courses for LNG firefighting in different companies.

3.3.10 Un-ignited Gas Cloud Mitigative Control

In case of an LNG spill, probability of fire is limited because of its narrow flammability range. Vapor cloud can form and until it is dispersed there is chance of fire. Adoption of active fire protection systems such as water curtains, portable gas drift detection system, high expansion foam and water monitor as mentioned earlier in active fire protection system.

3.3.11 Absence of Confinement and Congestion

In the design of LNG truck routes selecting one with less confinement and congestion can lower the consequences of an accident. In USA there are route and time restrictions for HAZMAT transportation [45]. Also there are restrictions for specific routes such as tunnel travel. But there is no specific selection of route for LNG. Since LNG vapor has a possibility of moving away with wind and finding a ignition source, special restrictions should be regulated to specify LNG transportation routes to avoid confined and congested area.

3.4 Analysis of Scenarios

In order to have the idea of how much area around a road will be affected by LNG fire or vapor dispersion, a consequence analysis has been done using PHAST software tool. This software is a comprehensive hazard analysis tool that can be used for the analysis of fire, explosion and toxic hazard. From a number of scenarios of LNG spill two scenarios have been chosen to determine effects of thermal radiation, concentration and overpressure at nearby areas.

3.4.1 Catastrophic Rupture

Due to structural failure or terrorist attack, the LNG tanker truck could be subjected to a catastrophic failure leading to a large spill or fireball. A consequence analysis was carried out to determine area affected by the vapor dispersion and thermal radiation from the rupture. Fireballs result from a turbulent fuel or two-phase vapor in air [46]. Basic features of static fireball models recommended by both TNO and HSE were adopted and implemented in the fireball modeling suite in PHAST [46]. In this study TNO model was used. The flame shape and duration are correlated as functions of the fireball fuel mass which is expressed mathematically as [46]:

$$M_{\text{Flammable}} = \begin{cases} M_{\text{Input}} & f_{\text{Vapour}} \geq \dfrac{1}{f_{\text{correction}}} \\ f_{\text{correction}} f_{\text{Vapour}} M_{\text{Input}} & f_{\text{Vapour}} < \dfrac{1}{f_{\text{correction}}} \end{cases}$$

Where:

$M_{Flammable}$ = Mass of fuel involved in the fireball [kg]

M_{input}=Total inventory released following vessel rupture [kg]

f_{vapour}=Mass fraction of vapour released following vessel rupture

$f_{correction}$=Mass correction factor (CCPS recommended value is 3)

From the mass of fuel involved in the fireball, surface emissive power is calculated using Robert's correlation which is:

$$E_f = \frac{f_s M_{\text{Flammable}} \Delta H_{\text{C}}}{4\pi r_{\text{Flame}}^2 t_{\text{Flame}}}$$

Where,

E_f=Surface emissive power of the flame [W/m^2]

f_s=Fraction of total available heat energy radiated by flame

ΔH_c=Net available heat for radiation [J/kg]

f_s is expressed in terms of the fuel's saturated-vapour/vessel-burst pressure, P_{sat} at the point of vessel failure.

$$f_s = 0.27\left(\frac{P_{\text{Sat}}}{10^6}\right)^{0.32}$$

Net available heat for radiation ΔH_c defined according to the HSE model is:

$$\Delta H_C = \Delta H_{Comb}$$

According to TNO model, ΔH_c is defined as [46]:

$$\Delta H_C = \Delta H_{Comb} - \left[\min\left(1, f_{vapour} f_{correction}\right) - f_{vapour}\right]\left[\Delta H_{Vap} + C_{p,Liq}\left(T_{Flame} - T_{Amb}\right)\right]$$

Where,

ΔH_{comb}= Heat of combustion of the fuel [J/kg]

$\Delta H_{vap=}$ Latent heat of vaporization of the fuel at its boiling point [J/kg]

$C_{p,Liq}$= Specific heat capacity of the fluid at constant pressure [J/kg/K]

For simplicity in the simulation composition of LNG was assumed to be 100% Methane. To obtain results for a worst case scenario Pasquill stability class was assumed to be F with a wind speed of 1.5 m/s. An LNG tank with 13000 US gallon of LNG was considered in this case. Figure 15 shows LNG concentration over time at a given distance after the rupture. It is observed that the concentration reaches upper flammability limit at around 50s and lower flammability limit at around 90s. Figure 16 shows maximum concentration footprint of LNG from a catastrophic rupture of an LNG tanker truck.

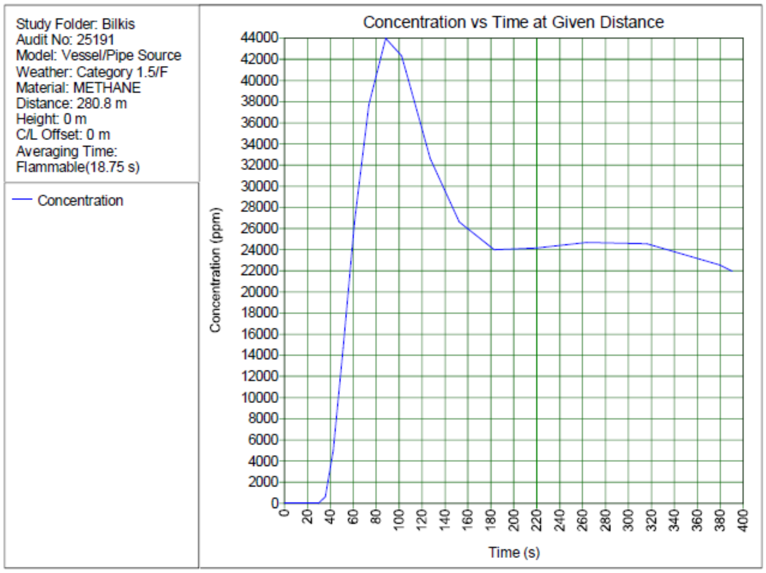

Figure 15: Concentration of LNG vs. time at a given distance

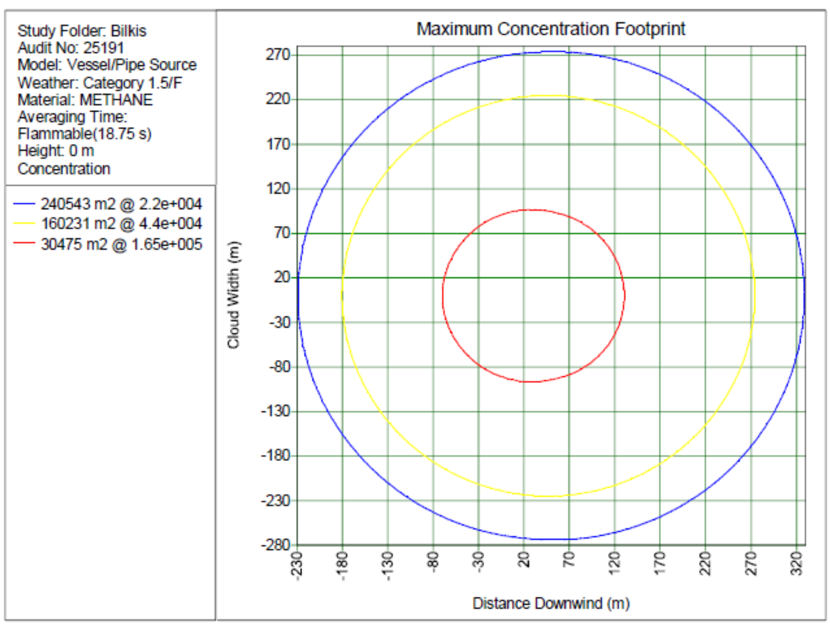

Figure 16: Maximum concentration footprint from catastrophic rupture of LNG tanker truck

Table 11 shows distances to different level of concentration of LNG after a catastrophic rupture. According to the instructional procedure of Swedish Gas Association, minimum evacuation distance in case of a LNG fire should be 300m [44]. From the results, it is observed that distances to a vapor concentration of Upper and lower flammability falls within the distance. Distance to vapor concentration of half the lower flammability limit is 334.662 m which is more than the required evacuation distance of 300 m. According to NFPA 59A 50% of lower flammability limit of LNG should not cross the property line [24]. If this regulation is considered for a road accident, distance to 0.5 LFL is out of the evacuation area.

Table 11: Distances to different level of concentration

Concentration (ppm)	Distance (m)	Area covered (m^2)
UFL (165000)	134.518	30475
LFL (44000)	280.754	160231
0.5 LFL(22000)	334.662	240543

In an event of a catastrophic rupture of an LNG tanker truck, LNG spill can result to a fireball if any ignition source is found. Figure 17 shows thermal radiation from the fireball vs. distance from the source.

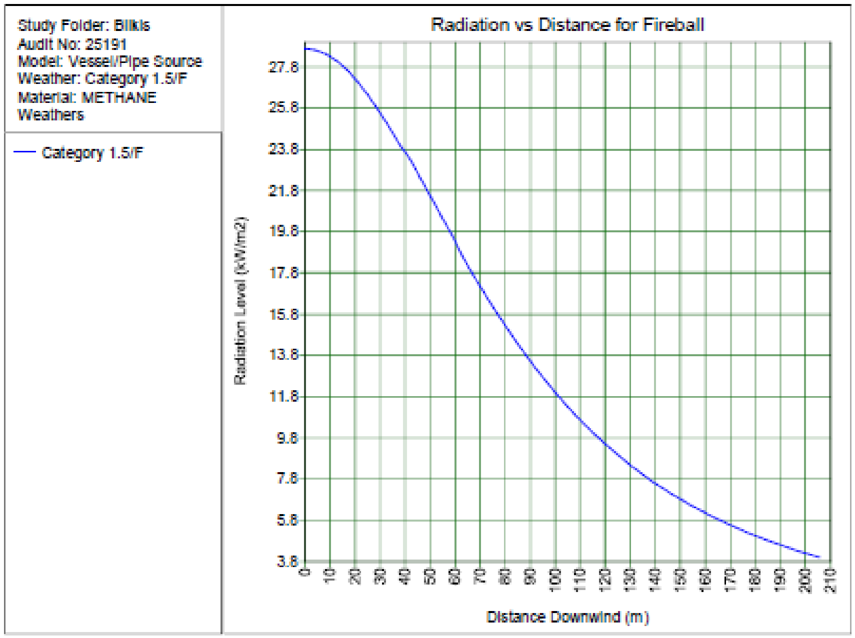

Figure 17: Thermal radiation from the fireball vs. distance

NFPA 59A standard specifies distances to a thermal radiation of 5KW/m^2 as a safe level of exposure [24]. Also in regulations of several other countries, this value has been selected as the threshold level for thermal exposure. In this heat flux a person would suffer 2nd degree skin burns on at least 10 % of their bodies within 30 seconds of exposure to the fire [24]. From a simulation of catastrophic rupture of an LNG truck, distances to different levels of radiation was found and provided in Table 12. The safe distance to thermal radiation of 5kW/m^2 was found to be 185 m.

Table 12: Distances to different thermal radiation levels

Radiation level (kW/m2)	Distance (m)
4	205.523
5	185.00
12.5	96.56
37.5	Not reached

In an event of LNG spill due to rupture of a tank, a delayed ignition can damage more since LNG gets more time to reach to the flammable concentration. Figure 18 and 19 shows overpressure vs. distance trend due to a late explosion and an early explosion. It is observed from the figures that in case of an early explosion, maximum overpressure is about 14.5 psi up to a distance of 40 m from the source of ignition and in case of a late ignition maximum overpressure reached approximately 370 m from the source. According to table 5 maximum evacuation distance provided by emergency responders is 300 m which is less than the distance with maximum overpressure was found. In case of an early ignition, overpressure at 300 m is approximately 0.5 psi which can cause minor structural damage like large and small windows shatter or occasional damage to window frames [47]. In case of a delayed ignition, there are more catastrophic consequences. Overpressure at 300 m in case of a delayed ignition was found to be 14.5 psi which can destroy building structure, heavy machine tools and cause rigorous damage to surroundings [47]. The estimation of these types of consequences requires more accurate data to get correct result.

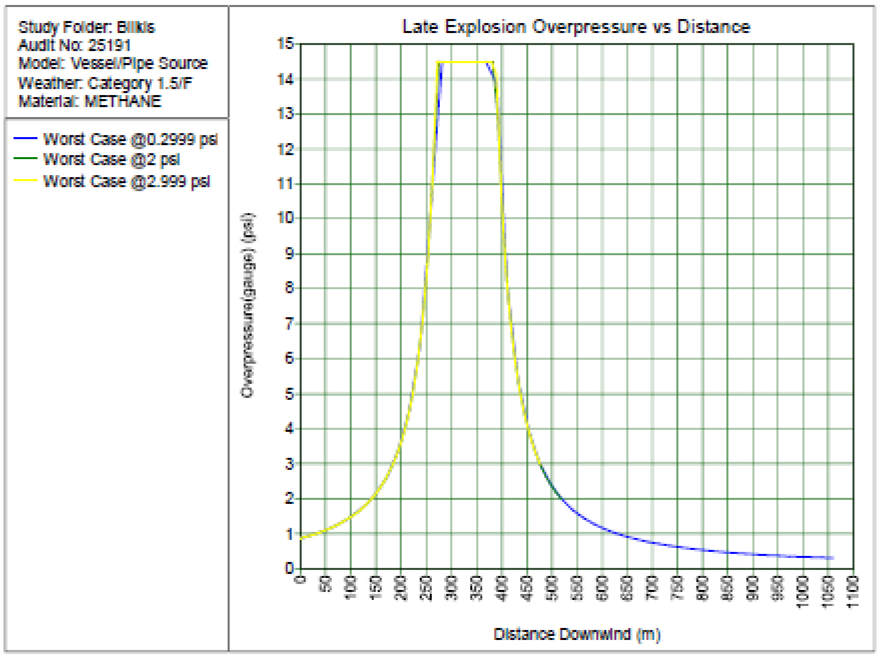

Figure 18: Late explosion overpressure vs. distance

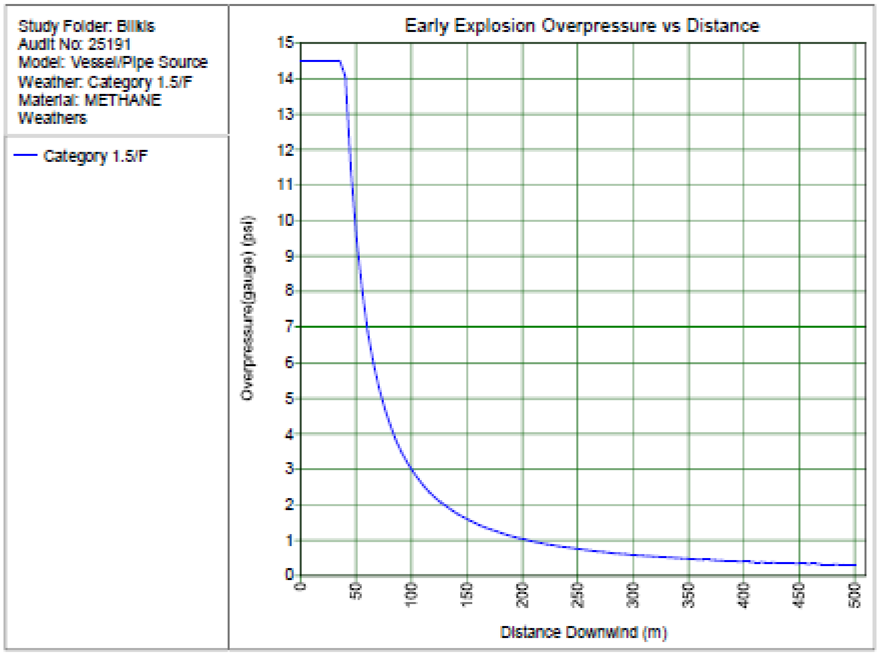

Figure 19: Early explosion overpressure vs. distance

3.4.2 LNG Pool Fire

After a release of LNG tank, a pool might form if there is sufficient discharge time. Figure 20 and figure 21 shows a radiation vs. distance for late pool fire and an early pool fire respectively. It was observed that maximum radiation level was 205 KW/m^2 for an early fire around a distance of 8m downwind. In case of a delayed ignition maximum radiation level was 220 KW/m^2 around a distance of 16m downwind.

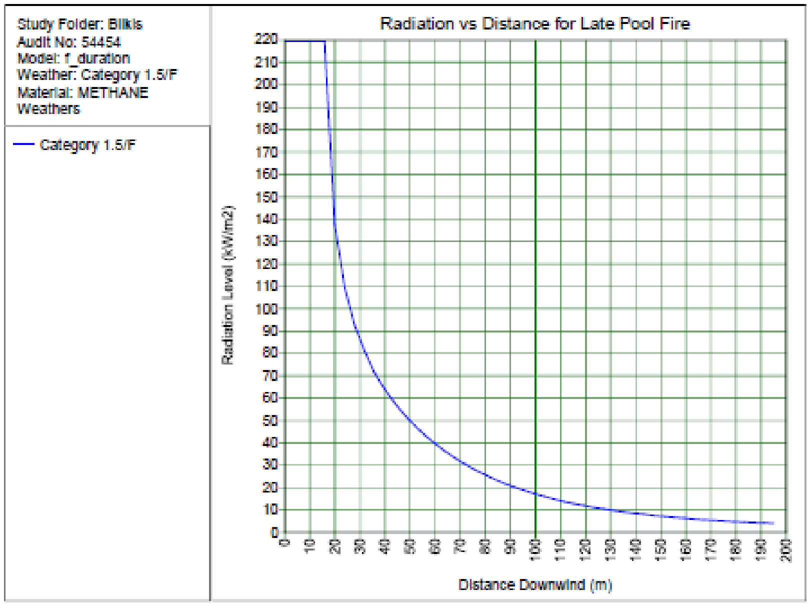

Figure 20: Radiation vs. distance for late pool fire

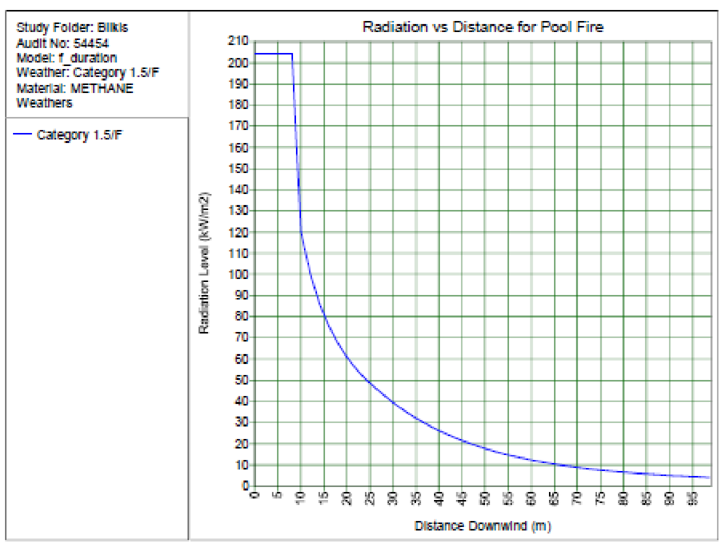

Figure 21: Radiation vs. distance for early pool fire

Also figure 22 shows centerline concentration of LNG with respect to distance downwind which does not show any significant hazard for the nearby area. Also figure 23 shows a flash fire envelope from LNG pool which shows the area associated with the flammable region.

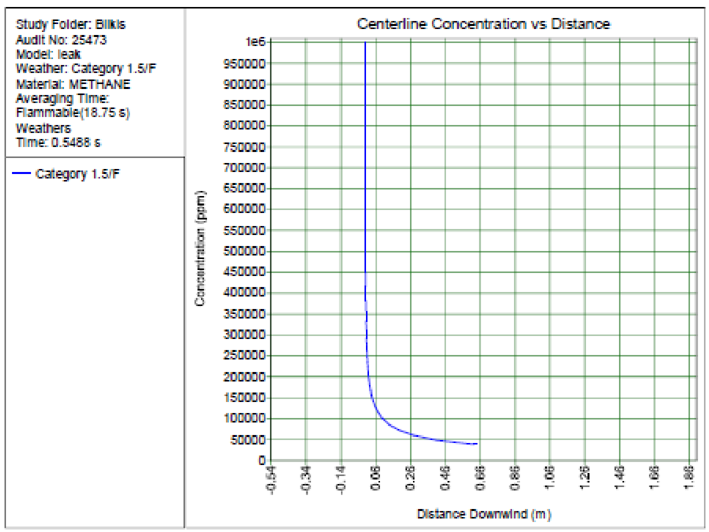

Figure 22: Centerline concentration vs. distance

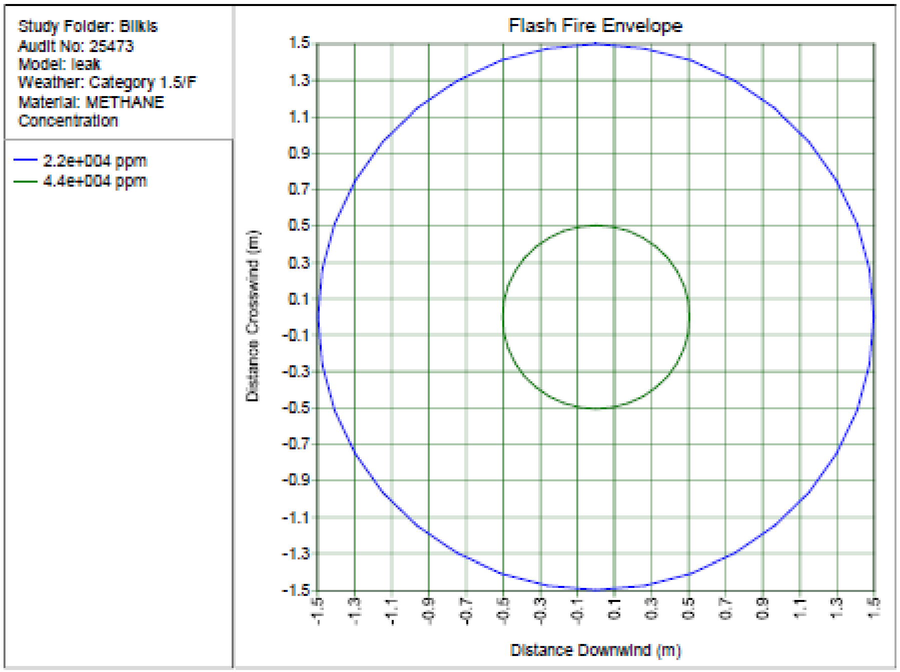

Figure 23: Flash fire envelope

Table 13 shows a comparison of distances to different level of concentrations of LNG for two different scenarios-catastrophic rupture and pool vaporization. It has been observed that the flammable region stays within 300 m which is the evacuation distance for LNG spill.

Table 13: Comparison of distances to different level of concentrations

Scenario	UFL distance (m)	LFL distance (m)	0.5LFL distance (m)
Catastrophic rupture	134.518	280.754	334.662
Pool vaporization	53.56	110.88	278.174

Also table 14 shows a comparison of distances to different level of thermal radiation for three different scenarios-catastrophic rupture, early pool fire and late pool fire. According to NFPA 59A, distance to a thermal radiation of 5KW/m^2 is considered as a safe level of exposure [24]. From the table it is observed that none of the distances exceeds the standard evacuation distance of 300 m.

Table 14: Comparison of distances to different level of thermal radiation

Scenario	Radiation (kW/m^2)	Distance (m)
Catastrophic rupture	4	205.523
	5	185
	12.5	96.56
	37.5	Not reached
Early pool fire	4	98.66
	5	89.68
	12.5	59.51
	37.5	31.2
Late pool fire	4	195.04
	5	176.977
	12.5	116.90
	37.5	62.44

The purpose of the analysis of these scenarios is to find out the requirement of evacuation planning around a road where an LNG tanker truck might get into an accident. To avoid any unwanted incident, residential planning should be done avoiding exposure zone of a release of LNG from a tanker truck in highways. The associated companies should plan their route avoiding highly residential areas. Route planning should also be done avoiding congested and confined area such as downtown, tunnel road and so on to avoid generation of a flammable cloud of LNG.

CHAPTER IV

CONCLUSION

4.1 Risk Management Strategy

Risks of an LNG spill from an accident of tanker truck can be reduced through a number of approaches such as reducing the potential and consequences of a spill, undertaking steps to ensure safety of the tanker truck, roadways, people and property. To ensure implementation of these approaches, a risk management strategy should be set which can be combination of prevention and mitigation techniques.

In this study, for risk management, a set of preventative and mitigative safety barriers were discussed to reduce the potential for and the hazards of an accidental or intentional spill. These strategies should be applied effectively, efficiently and economically to improve safety and security of LNG road transportation.

Preventative safety barriers that can function continuously include structural design, material selection, pressure and temperature design, passive fire protection. In US there are standard design requirements for structural design of LNG tanker truck provided by Department of transportation and some others. The standard is designed for vehicles carrying all cryogenic liquids and it works fine for LNG. Following the standards accurately will reduce the risk of any kind of accidental breach. For the design of pressure relief systems in the tanker truck standard federal regulations are followed. Properly following these standards can greatly reduce the chances of a cracked or failed valve leading to LNG spill.

Maintenance and inspection of a LNG tanker truck before its operation is an essential step for safe transportation. There are general maintenance and inspection standards available from Federal motor carrier safety administration (FMCSA) and federal regulations. But there is nothing specified for LNG tanker truck. Although the regulations work fine, more specified standards can reduce the risks of any future accident.

There is no specific certification testing found for LNG truck tanks. Although DOT specification 4-L is followed for the requirements of cryogenic liquids containers, studies should be carried out to observe any difference in tank trucks carrying LNG and other cryogenic liquids.

A significant number of road accident associated with LNG tanker trucks are caused by lack of driver proficiency. Even if the drivers have passed all necessary tests to get HAZMAT driver license, they are required to be trained according to federal regulations and also should have knowledge on the hazards and emergency response requirements for LNG.

Traffic rule enforcement is another important safety barrier to prevent incidents. Regulatory agencies should enforce on adopting rules on avoiding risk areas, confined areas, residential areas, heavy traffic areas and restrict hours of driving, speed control. Enforcement of using taco-graphs can help monitoring driving activities.

For prevention and mitigation of fire from an LNG spill, specified active and passive fire protection systems are used. For the fire protection activity, emergency responders should also be aware of the hazardous properties of LNG so that they can act promptly. In this study a consequence analysis was carried on to determine if the evacuation distance specified by emergency responders is good enough. From two scenarios-catastrophic rupture and LNG pool fire, it was seen that the amount of thermal radiation and overpressure are not dangerous in an evacuation distance of 300 m [39].

As we know LNG has a narrow flammability range (5%-15% concentration). So the possibility of a fire from LNG spill is very low unless there is any congestion or confinement. In a confined space LNG vapor gets time to reach to a flammable concentration and ignites in the presence of an ignition source. Therefore, some systems should be adopted to control and reduce the vapor cloud. Also route selection avoiding congested areas like residential areas, downtown or tunnels can help reduce the risks.

4.2 Conclusion

This study compiles almost all the relevant information on requirement of safe transportation of LNG tanker trucks. From the historical analysis, it has been observed that most of the incidents related to LNG road transportation were near miss incidents with insignificant spill or no spill of LNG. These near miss incidents should be accounted for and should be used as leading indicators to prevent further incidents. That is why a set of safety barriers were suggested to be considered for improvement.

This study provides an overview of the problem related to safety and security of LNG road transportation. But there should be more works carried out for more accurate measurement of consequences so that prevention and mitigations measures can be improved qualitatively and quantitatively.

4.3 Recommendations for Future Work

- LNG spill dispersion and fire modeling on land can be done for more accurate consequence estimation. For different type of location this analysis could be done to observe any significant difference.
- The bow-tie analysis can be extended by defining and weighing escalation factors to the safety barriers. Escalation factors are conditions that lead to increased risk.
- Consequence analysis of LNG spill can be carried out for different composition and to observe any significant difference.

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Appendix A

LNG Road Transportation Incidents (1971-2011) [16][17]

Date	Location	Description
1971	Waterbury VT	Blowout, 20 percent spill, no fire
1971	Warner NH	Driver fatigue, rollover cracked fitting, gas leak, no fire
1971	N. Whitehall, WI	Head on collision, gasoline and tire fire
1973	Raynham, MA	Trailer overturned , no fire
1973	New Jersey	rollover, damage to trailer, no fire
1974	New Jersey	faulty break , check valve cracked, no fire
1974	McKee City	Loose valve leaked
1975	Dalton, GA	rollover, no fire
1976	Chattanooga, TN	rollover, no fire
1976	Pawtucket, RI	car hit trailer, no fire
1977	Connecticut	truck hit by tow truck
1977	Waterbury, CT	hit by trailer, no loss of cargo
1977	Los Angeles CA	rollover, no fire
1981	Barnegat, NJ	excessive speed during turn, loss of product
1981	Lexington, MA	rollover, no fire, no product loss
1991*	South Sioux, NE	Breaking of the valve

1992	Unknown	A relay in the air conditioning system ignited a flammable methane-air mixture
1993	Everett, MA	trailer slide off the wheel, no fire
1994	Revere, MA	Trailer overturn at high speed
1997*	Canal Winchester, OH	Overpressure relief valve failed
1998*	Woburn, MA	Trailer travelling at high speed, no loss
1999*	Brighton, IL	Vehicular crash
2001*	Phoenix, AZ	Vehicular crash in high speed
2002*	Chattanooga, TN	Loose Closure Component or Device
2002	Catalonia, Spain	Trailer overturn and fire
2003	Newberry Springs, CA	Driver Fatigue, vehicle crash
2003	Woburn, MA	Trailer overturned , no leakage
2005	Reno, NV	LNG leak from fire-block valve
2006*	Everett, MA	Rollover accident
2007	Plymouth, IN	Vehicular crash, LNG leak
2007	Candiz, Spain	Slid down a bank, small fire caused by truck fuel
2010*	Tuba City, AZ	Drunk Driving
2011*	Long beach, CA	Defective component or device
2011	Istanbul, Turkey	Truck got stuck under a overpass
2012*	Ashville, AL	Human error

*PHMSA (Pipelines and Hazardous Materials Safety Administration)