Thermal Sciences

Energy Transport Solutions, LLC

ETS Movement of LNG in DOT-113 Tank Cars by Rail

Quantitative Risk Analysis (QRA) Considering DOT-113 Tank Car Position in Train and Train Speed

Exponent Project No. 1705991.000

Exponent®
Failure Analysis Associates®

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Prepared for

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Acronyms and Abbreviations

ALARP	As Low as Reasonably Practicable
ASME	American Society of Mechanical Engineers
°C	Degrees Celsius
DNV	Det Norske Veritas
DOT	U.S. Department of Transportation
ESD	Emergency Shutdown Device
ETS	Energy Transport Solutions, LLC
°F	Degrees Fahrenheit
FN	Frequency and Severity of Outcome
FRA	Federal Railroad Administration
ft	Feet
gpm	Gallons Per Minute
gal	Gallon
HAZMAT	Hazardous material
HSE	UK Health & Safety Executive
IR	Individual Risk
LEL	Lower Explosive Limit
LFL	Lower Flammable Limit
LNG	Liquefied Natural Gas
LOC	Loss of Containment
MAWP	Maximum Allowable Working Pressure
NFPA	National Fire Protection Association
PHMSA	Piping and Hazardous Materials Safety Administration
P&ID	Piping and Instrumentation Diagram
psig	Pounds per square inch gauge
QRA	Quantitative Risk Assessment/Analysis
SR	Societal Risk
Train Mile	Mile traveled by a train
UDM	Unified Dispersion Model
UFL	Upper Flammable Limit
yr	Year

Executive Summary

This report summarizes the Quantitative Risk Assessment (QRA) study conducted on the Energy Transport Solutions, LLC (ETS) proposed movement of liquefied natural gas (LNG) DOT-113 tank cars by rail in unit trains. In order to assist the process safety management of the operation, the focus of the study was to evaluate the risk for movement of the DOT-113 tank cars by rail transportation. This Executive Summary highlights Exponent's findings in the QRA. Further details are provided in the body of the report. Note that this Executive Summary does not contain all of Exponent's technical evaluations, analyses, conclusions, and recommendations. Hence, the main body of this report is at all times the controlling document.

E.1 QRA Overview

The scope of the QRA addresses unit train movements along one example route located in the Northeastern United States. The unit train movements were limited to mainline movements at high and low speeds. The hazard scenarios corresponded to accidents involving the DOT-113 type tank car, which is a double-walled vessel containing nominally 30,000 gallons of LNG. Accident event trees were constructed describing the necessary events and the frequency or probability of each step occurring to lead to a loss of containment (LOC) and ultimately a fire and/or explosion. Representative accident/failure frequency and probability values were developed from industry-available databases and FRA rail accident statistics.

Several conservative assumptions were applied during the analysis to estimate failure probabilities for the LNG DOT-113 type tank cars. The assumptions may be evaluated and changed based upon new information, and this may lead to different and likely lower (i.e., less conservative) failure probabilities (e.g., lower risk). The QRA assumed that each unit train includes LNG DOT-113 tank cars, starting at train position eleven (11), and one train movement was accomplished per day.

The QRA results are tabulated as a function of population density and train speed, providing per-route mile risk results. These per-route mile risk results can be used to determine the aggregate risk along a specific route for which population density and train speed along the route is known. An example route along the eastern portion of Pennsylvania was used to demonstrate the application of the per-route mile risk findings to determine aggregate risk along a route. Additionally, the per-route mile risk results can be used to determine distances to potentially sensitive targets, as will be discussed in more detail.

E.1.1 Evaluating the Risk

A commercially available software tool (PHAST Risk v6.7) was used to model the consequences of potential releases resulting in pool fires, flash fires, pressurized jet fires, and explosions, and to calculate the resulting Individual Risk (IR) and Societal Risk (SR) for the mainline. Typically, stakeholders (e.g., government agencies, investors, communities) set a threshold risk level that is deemed acceptable. This is called quantitative risk criteria and may vary from region to region and depends upon the type of facility or transportation activity. Currently, the U.S. Department of Transportation (DOT) Federal Railroad Administration (FRA) has not codified quantitative risk criteria for LNG hazardous materials transportation scenarios. Additionally, QRA analyses are not common regulatory requirements in the U.S. and no broadly-accepted risk criteria are employed by domestic communities or industries.

The quantitative risk criteria that may be considered by stakeholders for evaluating the IR presented in this report were referenced to those presented for stationary LNG plants in NFPA 59A *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG), 2016 edition*. The stationary LNG plant risk criteria are not directly applicable to rail movement of LNG, so international methods for adopting stationary facility risk criteria to transport risk are discussed for reference. The risk criteria presented in NFPA 59A are summarized in the following table.

Table E1. Summary of IR quantitative risk criteria developed from NFPA 59A (2016) and referenced in this report.

IR Criteria (yr^{-1})	Not Permitted
Zone 1: $IR \geq 10^{-5}$	Residential, office, and retail
Zone 2: $10^{-6} \leq IR < 10^{-5}$	Shopping centers, large-scale retail outlets, restaurants
Zone 3: $3 \times 10^{-7} \leq IR < 10^{-6}$	Sensitive Targets: churches, schools, hospitals, major public assembly areas

E.2 Findings

The QRA generated several findings regarding shipping LNG DOT-113 tank cars on the example route. The analysis required development of an accident model to calculate the release scenarios, which was then used to calculate the risk for the LNG DOT-113 movement along the route. The Societal Risk (SR) and Individual Risk (IR) for the mainline transportation were evaluated on a per-route mile basis as a function of train speed and population density. Finally, the Societal Risk was calculated for an example route using the per-route mile segments.

E.2.1 Accident Model

An accident model was developed as part of the QRA to address mainline movements of LNG DOT-113 tank cars in unit trains. For train movements, loss of containment of LNG from a DOT-113 was assumed to occur as the result of a derailment accident. LNG was assumed to be the only hazardous material involved in any incident. FRA data and Pipelines and Hazardous

Material Administration (PHMSA) data were used to build the accident model. A flowchart depicting the sequential steps of the accident model is provided in Figure E1. The sections of the report where each analysis block is described are listed in Figure E1.

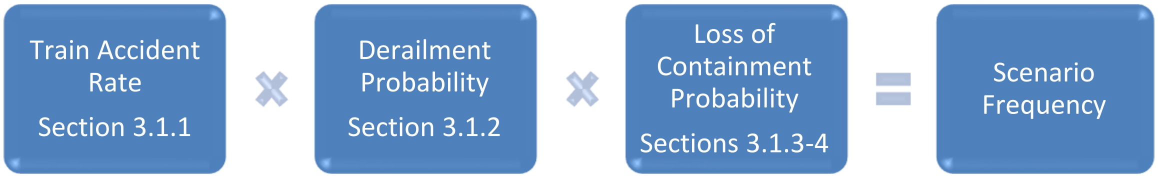

Figure E1. LNG DOT-113 train accident model overview.

FRA accident data from 1997 through 2016 were analyzed to develop train accident rates. Based on the available data, the train accident rate was calculated as accidents per train mile as shown in the table below.

Table E3. Train accident rates from FRA data.

	Statistic	1997-2016
Mainline	Total Non-Yard (Mainline) Train Miles	12.92×10^{9}
	Non-Yard Accident Rate (/train mile)	2.42×10^{-6}

The position in train derailment probability was evaluated for LNG DOT-113 tank cars as part of the QRA. A derailment model was employed where the probability that LNG DOT-113 tank cars would be derailed in an accident was related to the probability of the first car derailed and average number of cars derailed. It was assumed that a derailment would involve sequential cars starting with the first car derailed. The following two tables provide the probability of being the first car derailed versus position in the train and the average number of cars derailed in an accident.

Table E4. Representative probability of first car derailed for all railroad classes (1997-2016).

Statistic	Car Position in Train			
	1	11	21	31
Mainline Derailment Accident, Speed ≤ 25 mph	13.5%	1.87%	1.23%	1.02%
Mainline Derailment Accident, Speed > 25 to ≤ 50 mph	13.4%	1.20%	0.91%	0.80%

Table E5. Average number of cars derailed (1997-2016).

Statistic	No. of Cars
Mainline Derailment Accident Speed ≤ 25 mph	5
Mainline Derailment Accident, Speed > 25 to ≤ 50 mph	11

One train configuration was evaluated, which placed LNG DOT-113 tank cars in sequence from train position 11 on to the end of the train. If a train accident leads to a derailment, the probability relationship for multiple cars being derailed at high speed (> 25 to ≤ 50 mph) is shown in the table below. Similar relationships were developed for low speed accidents.

Table E6. Probability of having X number of LNG DOT-113 cars derail in the event of a train accident, where X is the number of LNG DOT-113s involved, for mainline train movements at high speed.

Number of LNG cars Derailed (X)	0	1	2	3	4	5	6	7	8	9	10	11
Probability	0.0%	13%	2.2%	3.1%	1.5%	1.6%	1.4%	1.5%	1.2%	0.9%	1.4%	72%

Finally, the loss of containment (LOC) was modeled using a probability versus quantity released relationship developed from analysis of historical PHMSA data. Since data are relatively sparse for DOT-113 tank cars in rail accidents, pressure tank car data was used as an analog to represent pressurized DOT-113 tank car failure probability. The probabilities are shown in the table below. The release scenario probabilities were combined with the probabilities of derailment for multiple cars in an event tree model to estimate the quantity released for each distinct outcome in the accident model.

Table E7 LOC probability from PHMSA pressure tank car incident data and equivalent release scenario for one LNG DOT-113.

Quantity Released in gallons	Probability	Release Scenario
≤ 100	0.955	No Release
100 < x ≤ 1,000	0.016	½-inch Leak
1,000 < x ≤ 30,000	0.026	2-inch Leak
> 30,000	0.003	Catastrophic

E.2.2 Mainline Risk

The risk posed by the LNG DOT-113s along the mainline was evaluated by calculating the Individual Risk and the Societal Risk for a one-mile section of the routes exposed to various population densities. Two speed ranges, low speed (≤ 25 mph) and high speed (>25 mph to ≤50 mph), were applied in the model to demonstrate the effects of train speed restrictions. One train configuration was evaluated, with only LNG DOT-113s from train position 11 to the end of the train.

The tables below compare the calculated risk metrics for low speed and high speed movement, respectively, along a one-mile section of the mainline for the low, medium and high population density (500, 11,000 and 20,000 people/mile^2). The figure compares the aggregate SR for the high speed and low speed train cases. The example route is 227 miles, represented by population densities as described in Section 7.2. The aggregate societal risk profile for the example route indicates a likelihood of observing one fatality approximately once every 200 years for high speed mainline transport and approximately once every 350 years for the low speed mainline transport.

Table E8. Summary of the risk metrics for mainline LNG DOT-113 car train movements at low speed.

Population density (people/mile^2)	SR Integral (total risk, yr^{-1})	Maximum IR (yr^{-1})	Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)
500	3.61×10^{-5}	9.47×10^{-7}	N/A	N/A	455
11,000	1.36×10^{-3}	1.14×10^{-6}	N/A	160	500
20,000	2.96×10^{-3}	1.24×10^{-6}	N/A	195	510

Table E9. Summary of the risk metrics for mainline LNG DOT-113 car train movements at high speed.

Population density (people/mile^2)	SR Integral (total risk, yr^{-1})	Maximum IR (yr^{-1})	Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)
500	8.15×10^{-5}	2.11×10^{-6}	N/A	382	569
11,000	3.06×10^{-3}	2.57×10^{-6}	N/A	430	615
20,000	6.63×10^{-3}	2.82×10^{-6}	N/A	448	632

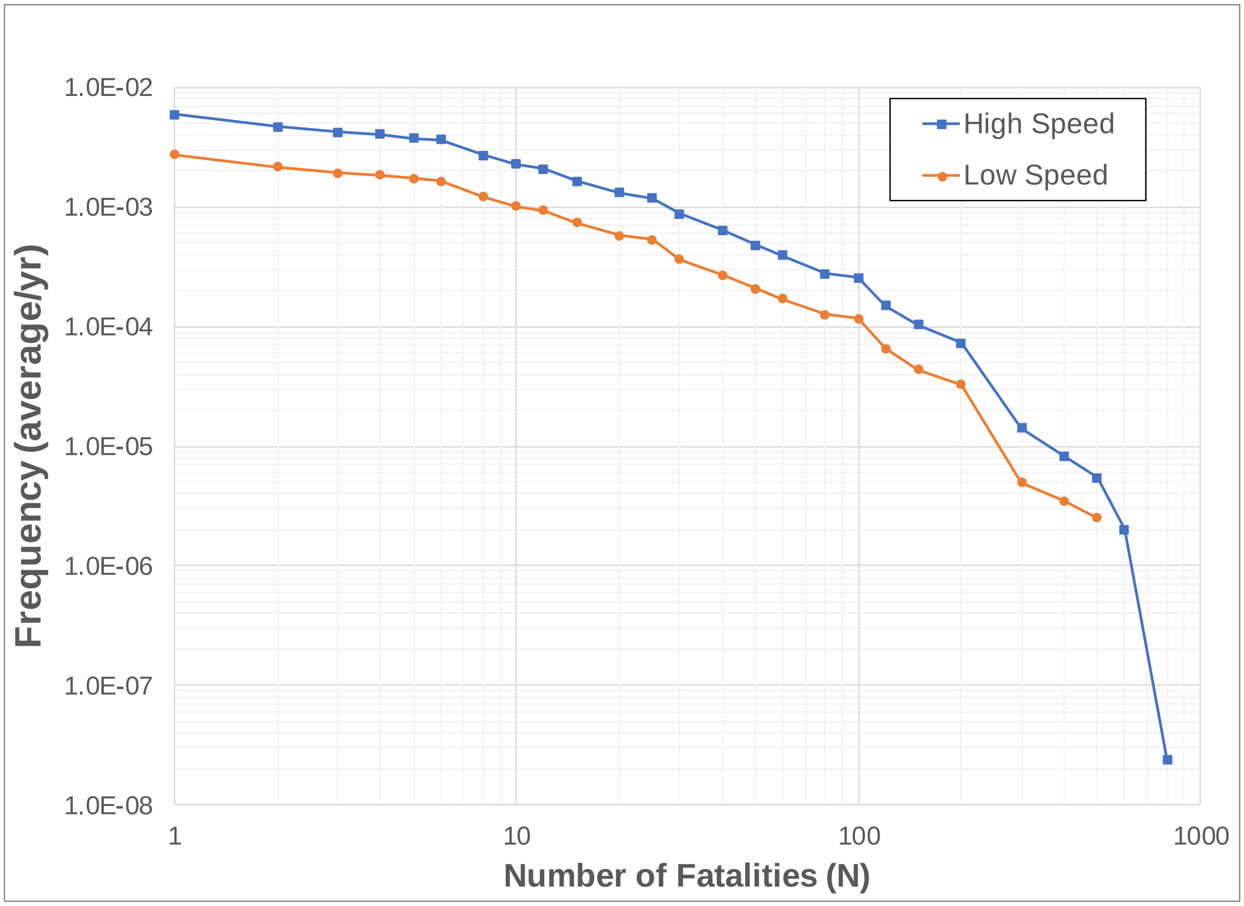

Figure E2. FN curve of the aggregate SR for the mainline train movement of LNG DOT-113s for the low speed case (up to 25 mph) and high speed case (greater than 25 mph and up to 50 mph) along the 227 mile long example mainline route. The population densities for the example route are described in Section 7.2.

E.3 Limitations of the Study

As requested by Energy Transport Solutions, LLC (ETS), Exponent conducted a Quantitative Risk Assessment (QRA) study addressing ETS movement of LNG DOT-113 tank cars in unit trains. The scope of services performed during this review may not adequately address the needs of other users of this report, and any use of this report or its findings, conclusions, or recommendations presented herein are at the sole risk of the user. The opinions and comments formulated during this assessment are based on observations and information available at the time of the study. The representation of NFPA 59A risk criteria in this report has been done for the purposes of comparing the transportation risk to a set of existing stationary facility quantitative risk criteria available in the U.S. and may not necessarily be appropriate or applicable for directly assessing acceptability of transportation risk. The assumptions adopted in this study do not constitute an exclusive set of reasonable assumptions, and use of a different set of assumptions or methodology might produce materially different results. Therefore, these results should not be interpreted as predictions of a loss that may occur as a result of any specific future event. Accordingly, no guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.

The findings and recommendations presented herein are made to a reasonable degree of engineering certainty. The methodology that was used in this report is based on mathematical modeling of physical systems and processes as well as data from third parties in accordance with the regulatory requirements. Uncertainties are inherent to the methodology and these may subsequently influence the results generated.

1 Introduction

Exponent conducted a Quantitative Risk Assessment (QRA) for unit train movement of liquefied natural gas (LNG) in DOT-113 tank cars for Energy Transport Solutions, LLC (ETS). The objective of the study was to determine the level of risk associated with the shipping of the LNG DOT-113 tank cars along mainline track routes.

The following considerations for risk analysis of LNG shipping by rail were addressed through this study:[1]

> A detailed risk analysis of the proposed operation along with appropriate mitigating measures. At a minimum, this risk analysis must include:
>
> a. Risks to the public and railroad workers from the proposed transportation of LNG, considering volumes transported, routes, operations on main lines, types of trains used, and any other relevant risk factors.
> b. Analysis of the specific structural characteristics (e.g., susceptibility, strength, ability to withstand exposure to heat) of the portable tanks proposed to be used, the number of tanks in a train, train speed, and position in train.
> c. Analysis of the thermophysical properties of LNG and its vapor, and expected multifaceted behavior of released LNG (fires, confinement-caused explosions, vapor fires, unconfined vapor cloud explosions, etc.) and the magnitudes of the different types of hazards presented by these properties.
> d. Considerations of the population density along the routes proposed.
> e. Assessment of both societal risks and individual risk to persons in the vicinity of the transportation routes and who may be adversely affected by an accident or incident involving a train transporting LNG.

To address these considerations, the risk of potential major incidents posed to surrounding populations was calculated during the QRA. The risk results have been presented in this report as tabulated distance to Individual Risk (IR) contours and graphically as Societal Risk (SR) through an incident frequency and severity of outcome (FN) curve, both on a per-route mile basis and as the aggregate SR along an example route.

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[1] Guidance for Preparing an Application under Title 49 Code of Federal Regulations Section 174.63 for Approval by the Federal Railroad Administration to Transport Liquefied Natural Gas by Rail in Portable Tanks.

1.1 Understanding Risk

Risk, simply defined, is the potential to lose something of value. Risk is evaluated by taking the product of event likelihood with the event outcome severity, and then comparing the product to some benchmark risk which is considered by the stakeholders as being acceptable.

The likelihood of an event can be estimated using experience relating to given equipment in similar service, industry data, or engineering approximations. A challenge of quantifying risk, or affixing a number to a particular risk level, is determining how to quantify the event outcome portion of the equation. For quantifying risk at industrial facilities and operations, the outcome of an event is typically evaluated as the potential for a fatality or multiple fatalities.

In evaluating the potential for fatality, two metrics are utilized to yield the risk: (1) Individual Risk (IR) and (2) Societal Risk (SR). Individual Risk is the frequency (yr^{-1}) where an individual with continuous potential exposure may be expected to sustain a serious or fatal injury.

Given that the LNG DOT-113 tank cars will be transported along long routes (e.g., hundreds of miles), release scenarios were modeled along the rail line on a per-route mile basis. IR contours cannot be succinctly represented for long routes such as this, but they are related to the population level along the line.[2] Thus, the highest risk along the mainline will occur at the portion of the track exposed to the highest populations.

Societal Risk (SR) is another method for evaluating the risk of a given process or operation. Unlike IR, the SR calculation considers the relationship between the cumulative number of potential fatalities (N) versus likelihood (F) from a series of potential events. The outcome of a SR analysis is a FN graph depicting annual frequency F on the y-axis and N fatalities on the x-axis, where F is the cumulative frequency for all scenarios having N potential fatalities. Whereas the IR calculation gives insight into the probability of having a fatality, the SR calculation gives the likelihood of a number of potential fatalities. This is especially important for evaluating scenarios with a large potential impact for loss of life, such as train derailments of flammable materials.

1.1.1 Developing Quantitative Risk Criteria

After quantifying risk and presenting the calculations as IR and SR for a given operation or process, the results are evaluated for tolerability (or acceptability). Typically, stakeholders (e.g., government agencies, investors, communities) have a threshold risk level that is deemed acceptable—known as quantitative risk criteria. Currently, the U.S. Department of Transportation (DOT) Federal Railroad Administration (FRA) has not codified quantitative risk

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[2] IR is a weak function of population due to the population density effect on the likelihood of ignition model.

criteria for LNG hazardous materials transportation scenarios.[3] Additionally, QRA analyses are not common regulatory requirements in the U.S. and no broadly-accepted risk criteria are employed by domestic communities or industries. The Dutch government and their respective regulatory agencies have been international leaders in utilizing QRA techniques for determining acceptability of fixed facilities and transportation routes. The approach for evaluating the risk results presented here is consistent with the Dutch guidance.

There are several foreign and several domestic examples of quantitative risk criteria.[4,5,6] Within these, there is a wide disparity in risk criteria for public exposure, with acceptable IR fatality probabilities ranging from 10^{-4} yr^{-1} (or a fatality per 10,000 years) to 10^{-8} yr^{-1} (or a fatality per 100,000,000 years). A broadly acceptable IR criterion from these international references is 10^{-6} yr^{-1}. Recommendations for QRA of LNG plants were issued in the National Fire Protection Association (NFPA) standard, NFPA 59A *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*.[7,8] In addition to including QRA as a risk assessment tool in the latest edition of NFPA 59A, the standard also includes quantitative risk criteria for fixed LNG facilities. NFPA 59A explicitly applies to LNG plants and stationary facilities; it does not apply to LNG transportation in DOT-113 tank cars. Thus, the quantitative risk criteria proposed in the standard are not directly applicable to rail shipping of LNG. However, these risk criteria are discussed here as one potential basis for quantitative risk criteria for rail shipping of LNG.

1.1.2 Individual Risk Criteria

During other rail LNG projects, the FRA requested that NFPA 59A quantitative risk criteria be used as a reference basis for the analysis. For IR, NFPA 59A identifies three “Zones” representing ranges of quantitative risk values. Each risk zone reflects general types of public occupancies recommended to be permitted within that risk zone. As the magnitude of the

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[3] Strang J, “Federal Railroad Administration Risk Reduction Programs,” United States Army Corps of Engineers Workshop on Tolerable Risk, March 18-19, 2008, Alexandria, Virginia.

[4] Appendix B: Survey of Worldwide Risk Criteria Applications, *Guidelines for Developing Quantitative Safety Risk Criteria*. Center for Chemical Process Safety, AIChE (2009).

[5] Cornwell JB and MM Meyer, “Risk Acceptance Criteria or ‘How Safe is Safe Enough?’” presented at II Risk Control Seminar in Puerto La Cruz, Venezuela, October 13, 1997.

[6] Ham JM, M Struckl, AM Heikkila, E Krausmann, C DiMauro, M Christou, JP Nordvik, “Comparison of Risk Analysis Methods and Development of a Template for Risk Characterisation,” Institute for the Protection and Security of the Citizen, European Commission, Directorate-General Joint Research Center (2006).

[7] NFPA 59A, *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*, 2016 edition, National Fire Protection Association.

[8] It should be noted that an older version – the 2001 edition of NFPA 59A – is one of the primary references for the requirements found in 49 CFR § 193, which provides the regulatory requirement for fixed LNG facilities operating in the U.S., and many of the 49 CFR § 193 codes reference NFPA 59A requirements directly. The 2001 edition of NFPA59A does not include requirements or suggestions for QRA.

calculated risk increases, the type of occupancy becomes more restrictive. The quantitative risk criteria for IR of LNG plants are reproduced in Table 1.

Table 1. Quantitative risk criteria for IR contours around stationary LNG plants as provided by NFPA 59A (2016).

Criterion Annual Frequency (yr^{-1})	Remarks
Zone 1 IR > 10^{-5}	Not permitted: Residential, office, and retail Permitted: Occasionally occupied developments (e.g., pump houses, transformer stations)
Zone 2 $10^{-6} \le IR < 10^{-5}$	Not permitted: Shopping centers, large-scale retail outlets, restaurants, etc. Permitted: Work places, retail and ancillary services, residences in areas of 7,250 to 23,300 persons/mile^2 density
Zone 3 $3 \times 10^{-7} \le IR < 10^{-6}$	Not permitted: Churches, schools, hospitals, major public assembly areas, and other sensitive establishments Permitted: All other structures and activities

For LNG release scenarios, the magnitude of the risk generally increases as the observation point is moved closer to the railroad. The distance to each risk level identified in Section 7 is a result of the compilation of the outcomes calculated from an event tree consisting of many potential fire and explosion events. The resulting IR contours are provided in tabular form as a function of population density and train speed.

Based on NFPA 59A Zone 3 being the most restrictive zone, any IR values that are less than 3×10^{-7} yr^{-1} are not of concern for the analysis in this report, thus these contours are not reported. The IR ranges and associated criteria appear to be based on guidance provided by the Health and Safety Executive in the UK for QRA[9] and do not account for the factors typically considered in a transportation risk analysis. However, the commonly acceptable level of IR for transportation risks for sensitive populations is 10^{-6} yr^{-1}, which is the upper threshold for NFPA 59A Zone 3.[10] IR contours and distance to those contours for both 10^{-6} and 3×10^{-7} yr^{-1} are provided in the results.

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[9] "B.1 Evolution of Land Use Planning Criteria in the UK," in Guidelines for Developing Quantitative Safety Risk Criteria, American Institute of Chemical Engineers, Center for Chemical Process Safety (2009).

[10] See Section 5.4 in reference: Ham JM, M Struckl, AM Heikkila, E Krausmann, C DiMauro, M Christou, JP Nordvik, "Comparison of Risk Analysis Methods and Development of a Template for Risk Characterisation," Institute for the Protection and Security of the Citizen, European Commission, Directorate-General Joint Research Center (2006).

1.1.3 Societal Risk Criteria

Based on a review of the literature and an understanding of the risk analysis framework, it is apparent that stationary facility SR criteria are not appropriate for evaluating the transportation or shipping risk of hazardous materials along a route. For the risk of a stationary facility, all consequences (e.g., toxic release, fires, and explosions) are limited to the region surrounding the facility, which may have a characteristic dimension on the order of 1 km with a fixed surrounding population. If the same consequences are applied to a tanker truck or rail car transportation route, then the geographic region where those consequences may be manifest can be much larger and the surrounding population may vary. Additionally, for stationary facilities there may be green space (i.e., no permanent population) around the site and/or a considerable amount of property under their control; however, concerning transport applications, this standoff distance is greatly reduced or may not exist.

The aggregate societal risk for a transportation route is directly proportional to the length of the route. For example, a 10 km route would have 10 times the risk of a stationary facility all else being equal; a 100 km route would have 100 times the risk, and so on. The total aggregate SR for a shipping route is presented on an FN graph without using quantitative risk criteria due to this aggregate risk versus distance relationship. Using a quantitative risk criterion that is based on a stationary facility will inherently limit the risk tolerability of routes to those that are similar in dimensions to a stationary facility. To address this limitation, the international regulations and guidance documents employ a scaled approach to compare the highest risk sections of a transportation route to stationary facility quantitative risk criteria by applying SR criteria on a per unit length of route (i.e., per route kilometer) basis.[11]

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[11] For example, see Section 3.3.5 “Calculation and presentation of results” in the Dutch Purple Book, which states, “According to current regulations the Societal Risk has to be calculated and presented per kilometre of transport route. For shunting yards this does not of course apply.” *Guideline for Quantitative Risk Assessment, Part Two: Transport* (Dutch Purple Book), Publication Series on Dangerous Substances, Ministerie van Verkeer en Waterstaat (2005)

1.2 LNG Hazards

LNG poses unique hazards relative to other non-pressurized liquid fuels. LNG has a shipping identification number of UN1972 for refrigerated cryogenic methane. LNG, comprised primarily of methane, has a flammable range when mixed with air in concentrations of approximately 5% to 15%; outside of this range, the fuel will not burn. The liquefaction of natural gas is achieved by cooling the material to its normal boiling point, - 260°F. This is unlike other low molecular weight hydrocarbon fuels, like propane, which can be liquefied by pressurization. At the boiling point temperature, LNG does not need to be stored under pressure but it must be insulated to avoid excessive boiling due to heat transfer. As the liquid boils, it does so at its constant, low boiling point temperature. To avoid excessive pressure buildup under extended duration storage conditions, LNG DOT-113 containers will vent low volumes of natural gas to the atmosphere via a pressure relief valve.

The cryogenic temperatures of LNG pose unique hazards to rail personnel. Due to a large difference in temperature, the rapid transfer of heat from an object into the cryogenic liquid can cause burns if direct contact with skin occurs or if PPE is inadequate to prevent cold-temperature injury due to an exposure. Additionally, large spills of the liquid onto metal structures can cause embrittlement and fracturing. Methane is odorless and LNG contains no odorant (unlike residential natural gas supplies), making detection difficult without a flammable gas detector device.

The behavior of a spill of LNG is unique due to the cryogenic temperature of the liquid. For example, a spill of LNG will vaporize rapidly when it contacts ambient air and even faster when in contact with warm solids such as the ground. The cold vapors may condense humid air, causing fog formation and decreased visibility. After vaporization, the cold vapors are denser than ambient air, will tend to stay close to the ground as they disperse, and will get pushed by prevailing winds. The dense vapors can travel great distances without significant dilution, as the mixing with ambient air is limited near the ground, and the vapor will tend to accumulate in low spots or trenches along the ground.

The operational hazards of handling LNG were not considered in this study; only large scale releases and ignition that could cause fire and explosion events were explored. The specific fire and explosion scenarios, as well as release, ignition, and consequence probabilities will be discussed in more detail later in this report.

2 Systems Description

Unit train LNG DOT-113 tank car movements were evaluated along mainline rail track as a function of train speed and exposed population density. The QRA assumed an average daily movement rate of eleven or more DOT-113 tank cars with a capacity of 30,000 gallons. As will be discussed below, although more containers may be shipped within the same train, the overall risk is adequately represented by modeling this annual average movement capacity.

The following sections will provide more details on the DOT-113 tank cars and the proposed train route.

2.1 DOT-113 Rail Tank Cars

The LNG will be transported in DOT-113 cryogenic liquid rail tank cars. The DOT-113 is typically comprised of an interior pressure vessel to contain the cryogenic liquid, surrounded by an exterior tank with the intermediate space insulated by vacuum. The interior pressure vessel is commonly constructed of stainless steel and fabricated to DOT requirements.

The DOT-113 containers are capable of LNG service. Example design parameters are listed in Table 2.[12]

Table 2. DOT-113 tank container parameters used in this study.

Parameter	Value
MAWP (psig)	90
LNG Capacity (gallon)	30,000 (nominal)
Net Volume (gal)	10,830

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[12] LNG Tank Car SR-603, Bulk Transport Unit, Chart Industries. <www.ChartLNG.com>

2.2 LNG DOT-113 Movement Routes

Movements were evaluated along mainline track at high speeds (> 25 mph and ≤ 50 mph) and low speeds (≤ 25 mph). The risks were calculated at varying population density for 1-mile sections of track. The per-mile risk results were then used to estimate the aggregate risk for an example 227 mile track along eastern Pennsylvania. The total estimated track length and train mileage for the example route, assuming each route is travelled once per day, every day of the year, are supplied in Table 3.

Table 3. Example route and estimated mileage.

Route	Route Length (track miles)	Estimated Total Annual Route Length (train miles)
Route 1	227	82,855

3 Methodology

The QRA was conducted by applying PHAST Risk (SAFETI) software to evaluate a series of accident scenarios involving the transportation of a unit-train of LNG in DOT-113s along mainline track routes. The objective of the analysis was to quantify the Individual Risk (IR) and Societal Risk (SR) for various populations surrounding the rail lines along 1-mile sections of track.

Engineering and administrative systems that may be employed to reduce the likelihood or the severity of releases along the route were not considered in this analysis (unless otherwise stated). The objective of this QRA study is to provide the conservative maximum baseline risk levels for transporting unit trains of LNG DOT-113 tank cars along mainline routes.

A potential incident resulting from a loss of containment of LNG would require a sequence of events to occur. QRA takes this sequence of events and assigns a frequency to the initiating event and conditional probabilities of occurrence for subsequent events. One initiating event may lead to several potential outcomes, not all of which create a potential hazard. QRA models the sequence of events through event trees with appropriate complexity to describe the most likely event outcomes. Each outcome, e.g., the consequence of a release of LNG, is then modeled to determine the impact of the flammable release event. For releases from a fixed location, the source for the release is modeled as a pseudo point source. For releases that may occur along a route, e.g., line of road for rail, the source for the release is modeled at periodic intervals along the route. In terms of a QRA for LNG transportation, only the potential flammable release hazards were evaluated for LNG. The outcome, which may be injury or fatality of onsite personnel or the public, is related not only to the physical event consequences (e.g., size of a flash fire), but also to the potentially impacted population. The PHAST Risk software incorporates the surrounding population, the phenomenological release and consequence models, event tree-derived frequencies for each outcome, and industry-accepted population impact models to calculate the IR and SR for facilities and transportation operations.

The key parameters that must be evaluated to perform the QRA, from beginning (accident occurs) to end (a potential fatality is realized), include:

1. Accident—in order for the identified consequence to occur, a vessel containing LNG must first be involved in an accident. The likelihood of an accident involving the unit train of LNG DOT-113s is estimated.
2. Loss of Containment—the hazards evaluated here concern the flammable nature of the LNG fuel vapors. In order for a fire or explosion to occur, there must be a loss of containment (LOC) event involving the LNG vessel. The LOC probabilities and leak size distributions are estimated.

3. Formation of flammable atmosphere—following an LOC, the LNG must vaporize and the flammable vapors must mix with air in the appropriate concentrations. The size and downwind distance of the flammable clouds are calculated in PHAST Risk.
4. Ignition of flammable atmosphere—the flammable atmosphere must be ignited in order for a fire or explosion to occur. The ignition probabilities, as a function of time, distance, and population as the flammable cloud is formed and dispersed, are calculated in PHAST Risk.
5. Exposure to a population—the populations that may be affected by an incident involving LNG are estimated using U.S. Census data, and the population data is input into PHAST Risk for calculation of the IR[13] and SR. The potential for a fatality, given a specific thermal event (i.e. flash fire, pool fire, jet fire, or explosion), is calculated in PHAST Risk.

Figure 1 provides a representative event tree starting with the initiating event (train accident) carried through to a flammable event to illustrate the general probabilistic calculation approach for each type of outcome.[14] A detailed discussion of these key QRA parameters, as considered and evaluated for the proposed ETS shipping of DOT-113 project, is provided in subsequent sections.

Given the nature of the project, several variables were approximated or estimated to provide this QRA. For example, accident rates involving LNG DOT-113 tank cars via rail in the US are not available. Currently, the Federal Railroad Administration (FRA) has not codified guidelines for acceptable risk to individuals or society. Thus, the quantitative risk criteria for stationary LNG facilities provided by NFPA 59A were used to establish risk levels of potential concern. The representation of NFPA 59A risk criteria for IR in this report has been done for the purposes of comparing the transportation risk to a set of related criteria and may not be appropriate or directly applicable for assessing acceptability of transportation risk.

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[13] Note that IR assumes continuous potential exposure of personnel or the public; thus, it is not directly related to population like SR. However, population density is an input to the probability of the ignition model employed in the software; hence, IR is a function of population.

[14] The example event tree depicts an initiating event and event tree probabilities for the transport of LNG DOT-113s along the mainline track, for train speeds less than 25 mph. See the following sections for more details. The event tree for mainline track with train speeds 25-50 mph can be found in Appendix B.

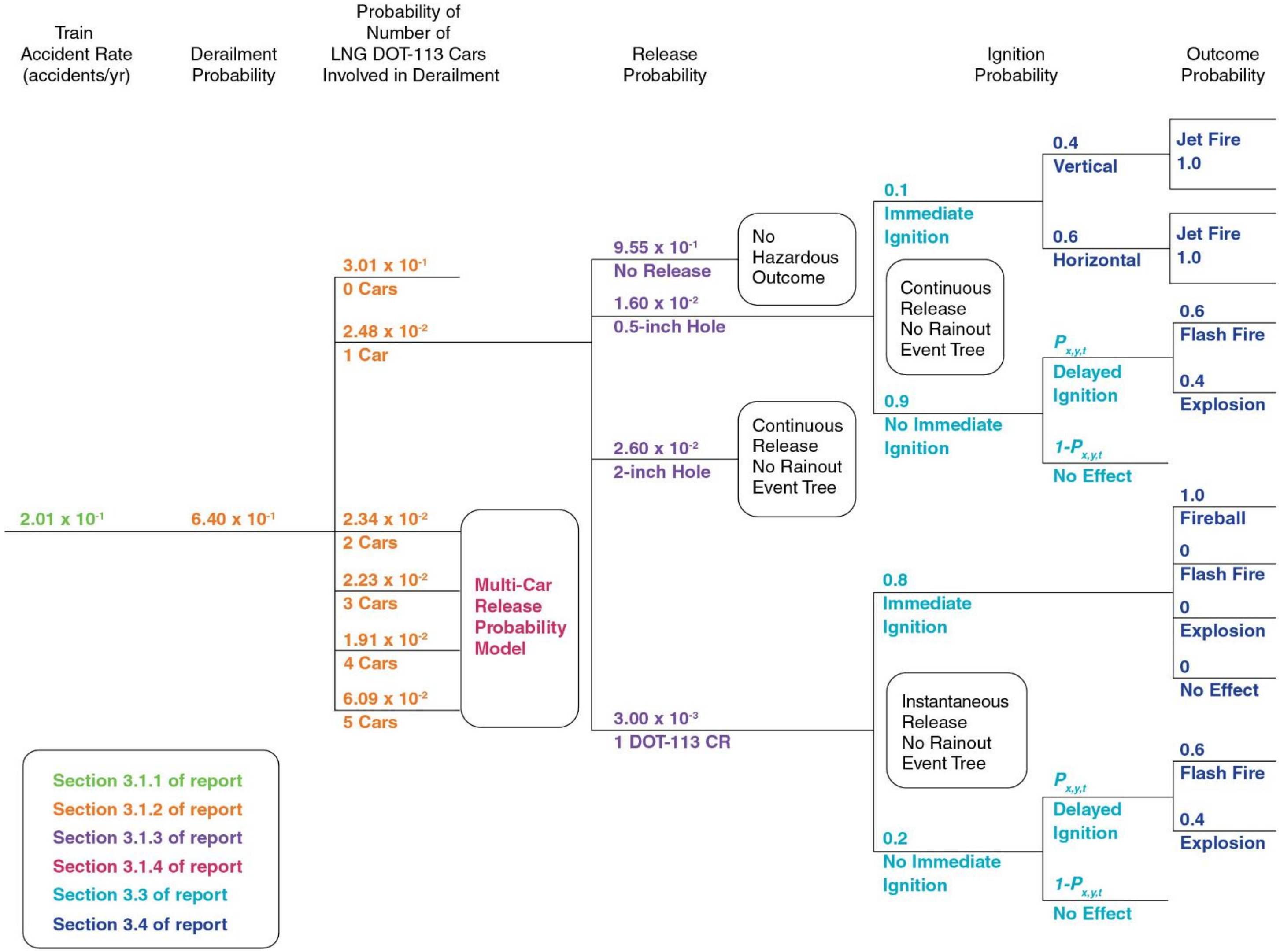

Figure 1. Representative event tree illustrating the relationship between the frequency of train accident and conditional probabilities of subsequent events in the analysis.

3.1 Estimating Accident Rates and LOC Probabilities

The sequence of events leading to a loss of containment (LOC) of LNG in the analysis starts with an accident involving a train containing LNG DOT-113s. The rate of mainline train accidents was applied to shipping along the routes. No QRA-ready databases of train accidents and LOC probabilities existed for LNG DOT-113s. Thus, representative accident/failure frequency and probability values were developed from industry-available databases and FRA rail accident statistics. An accident model was developed to calculate the LOC frequency for rail movements in the QRA. As shown in Figure 2, the train accident rate was first calculated. Then, given an accident, the probability of derailment for various considerations was calculated. Ultimately, the probability of LOC was calculated. Multiplying these three values together yielded the LOC rate for a given scenario. The bases, assumptions, and results are discussed in the following sections.

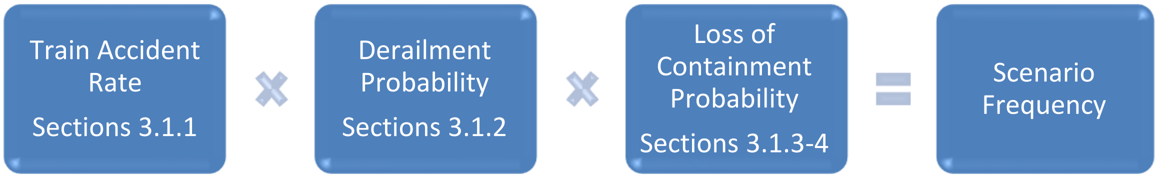

Figure 2. LNG DOT-113 train accident model overview.

3.1.1 Train Accident Rates

LNG shipping by rail is historically uncommon in recent U.S. rail industry history; thus, accident data for the movement of LNG in DOT-113 rail cars do not exist. Exponent analyzed publicly-available data from the FRA to estimate train accident rates for the QRA. For the purposes of this analysis, potential train accidents were only considered to occur along the line of road. The following discussion will provide an overview of application of the available data to estimating potential LNG DOT-113 train accident rates.

The FRA Office of Safety Analysis maintains an online database that provides historical accident and failure rate data for the rail industry.[15] Accidents in the database include broken equipment, highway grade crossing collisions, train collisions, and derailments. The FRA industry-wide database for train accidents with reportable damage data[16] was first queried and downloaded for all accident reports during the twenty year period from 1997-2016, yielding a

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[15] Accessible via safetydata.fra.dot.gov.

[16] FRA Office of Safety Analysis, Report 3.16 – Summary of Train Accidents with Reportable Damage, Casualties, and Major Causes.

total count of 65,940 accidents. The accidents are identified in the database by category and include multiple types of collisions, explosions, fires, other impacts, and other events. These types of accidents are consistent with the events necessary to lead to an LOC of LNG from a DOT-113. The FRA data was filtered for all accidents from 1997-2016 (all railroad classes), and the results were analyzed to determine accident frequency for mainline accidents and derailment probability at two different speeds. The values are summarized in Table 4 for accidents and derailments from this data. This data was used to determine accident frequency, as will be discussed below.

Table 4. Train accident rates from FRA data.

	Statistic	1997-2016
Mainline, Speed ≤ 25 mph	Total Accidents	22,192
	Total Derailments	14,199
	% of All Accidents	33.65%
	Probability that Derailment Occurs	64.0%
Mainline, Speed > 25 to ≤ 50 mph	Total Accidents	6,580
	Total Derailments	3,501
	% of All Accidents	9.98%
	Probability that Derailment Occurs	53.2%

The raw accident numbers were then divided by train mileage to develop accident frequency estimates as accidents per train mile for the QRA. Operational data tables provided by the FRA were used to determine the total number of mainline[17] train miles for the period from 1997-2016 for all classes of railroad represented in the data.[18] The operational data tables did not subdivide the mainline train miles according to track speed; thus, only the total accident frequency per mainline train mile for all trains could be calculated. This single mainline train accident frequency value was applied to all mainline train movements regardless of train speed. By applying the total rail industry accident frequency, this provides a reasonable representation of the accidents per train mile for any subset of the data such as accidents at speeds over 25 mph, or any other subdivision. Using the total accident and total mileage values, the accident frequency (on a per train mile basis) was then calculated. The average accident frequency was found to be 2.42×10^{-6} (accidents/train mile) for the mainline travel. The 20-year data was used throughout the analysis due to the relatively large number of data points that provide a larger confidence in the position-in-train derailment probabilities (discussed in Section 3.1.2). The results are summarized in Table 5.

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[17] All "Non-yard" miles were assumed to be mainline miles for the purpose of this analysis.

[18] FRA Office of Safety Analysis, Report 1.02 – Operational Data Tables.

Table 5. Train accident rates from FRA data.

	Statistic	1997-2016
Mainline	Total Non-Yard (Mainline) Train Miles	12.92×10^{9}
	Non-Yard Accident Rate (/train mile)	2.42×10^{-6}

The mainline accident frequencies[19] from Table 5 were then multiplied by the total number of annual train miles estimated for the example route (Table 3) to arrive at the yearly accident frequency (accidents per year) used in the calculations for the route. A summary of the calculated annual accident rate for the example route is provided in Table 6.

Table 6. Calculated annual accident frequencies for the example ETS mainline route.

Route	Estimated Total Annual Route Length (train miles/yr)	Accident Frequency (accident/train mile)	Calculated Annual Accident Frequency (accident/yr)
Route 1	82,855	2.42×10^{-6}	2.01×10^{-1}

3.1.2 Derailment Probability for LNG DOT-113 Cars

The train accident values shown above provide an estimate of the frequency that a train accident will occur somewhere along the example ETS route. However, a train accident doesn't necessarily lead to a condition where an LOC of an LNG DOT-113 may occur. Therefore, it was assumed that only train accidents leading to the derailment of cars could potentially result in an LOC. The 20-year accident data was analyzed to determine the probability that a train accident will lead to a derailment of any of the rail cars for one of two cases: (1) mainline movement with train speeds from 25 mph up to 50 mph, and (2) mainline movement with train speeds equal or less than 25 mph. As listed in Table 7, the calculated derailment probabilities were found to be 64.0% for mainline movement with train speeds less than or equal to 25 mph and 53.2% for mainline movement with train speeds between 25 mph and 50 mph. These are the probabilities of at least one car being derailed in a train accident; however, this probability does not guarantee that the derailment will involve LNG DOT-113s. The calculation of the probability that an accident-leading-to-derailment involves LNG DOT-113s is addressed in the next section.

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[19] Note that the terms frequency and rate are used interchangeably.

Table 7. Analysis of train accidents from FRA data.

	Statistic	1997-2016
Mainline, Speed ≤ 25mph	Total Accidents	22,192
	Total Derailments	14,180
	% of All Accidents	33.7%
	Probability that Derailment Occurs	64.0%
Mainline, Speed from > 25 to ≤ 50 mph	Total Accidents	6,580
	Total Derailments	3,501
	% of All Accidents	9.98%
	Probability that Derailment Occurs	53.2%

3.1.2.1 Probability of Number of LNG DOT-113 Cars Derailed

Not all accidents-leading-to-derailment will involve an LNG DOT-113 car. Several factors are expected to affect the likelihood that an LNG DOT-113 car is derailed including: (1) the position of the LNG DOT-113 car(s) within the train and (2) the number of LNG DOT-113s grouped together. In this analysis, it was conservatively assumed that the unit-trains of LNG DOT-113s started at train position eleven (11) and continued throughout the remainder of the train. The historical FRA accident data was analyzed to develop a model for estimating the probability of derailment of an individual car versus its position in the train.

The probability of derailment for one or more LNG DOT-113 cars is dependent on the position of the first car derailed in the train, the average number of cars derailed during an accident, and the location of LNG DOT-113s in the train. These parameters are expected to be affected by the train speed, which was explored here using the FRA 20-year accident data.

The FRA 20-year accident data from 1997-2016 was first filtered to include only mainline accidents. The mainline accidents were then further split into either low speed mainline accidents with train speeds less than or equal to 25 mph or high speed mainline accidents with train speeds greater than 25 mph up to 50 mph. Next, the accidents were filtered in the database by including only accidents resulting in derailment. The average number of cars derailed for each of the two cases was then calculated (rounded up to whole numbers):

Case 1. Mainline derailments, speed ≤ 25 mph, average number of cars derailed = 5

Case 2. Mainline derailments, speed 25-50 mph, average number of cars derailed = 11

Based upon the dynamics of a derailment, it was assumed that in an average derailment, the first car would derail plus the immediately following sequence of *n*-1 cars would derail, where *n* is the average number of cars derailed. Regarding mainline movements, lower speed derailment accidents involve fewer cars on average than higher speed derailment accidents.

The filtered data for each of the three cases is plotted in a histogram based on the position of the first car derailed in Figure 3 for train speeds between 25 mph and 50 mph and Figure 4 for train speeds less than or equal to 25 mph.

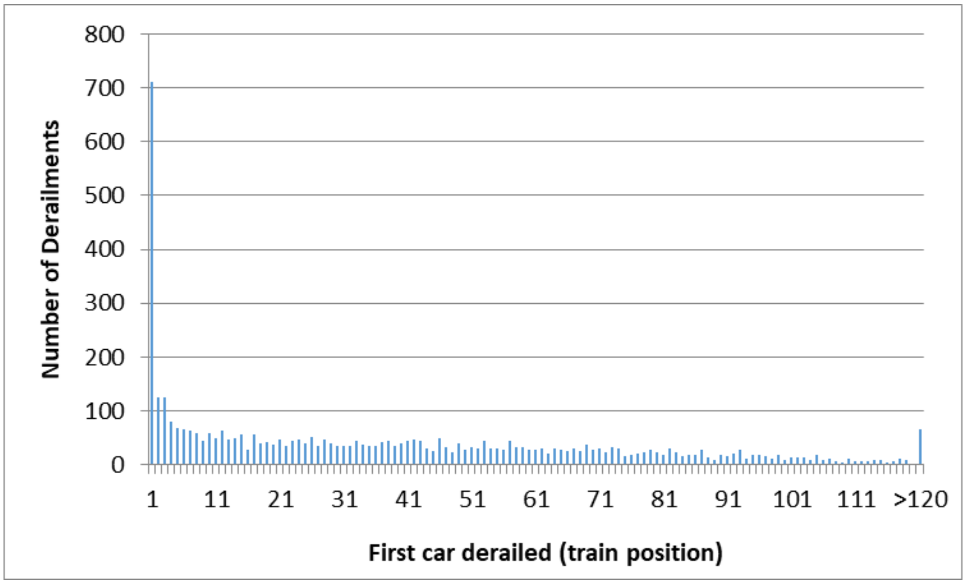

Figure 3. Frequency (count) of the first car position-in-train for mainline derailments with train speeds greater than 25 mph up to 50 mph (total count equals 3,501 derailments).[20]

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[20] Note that the value at the > 120 car position in the histogram represents the sum of all cars from 120 up to 200 listed in the database.

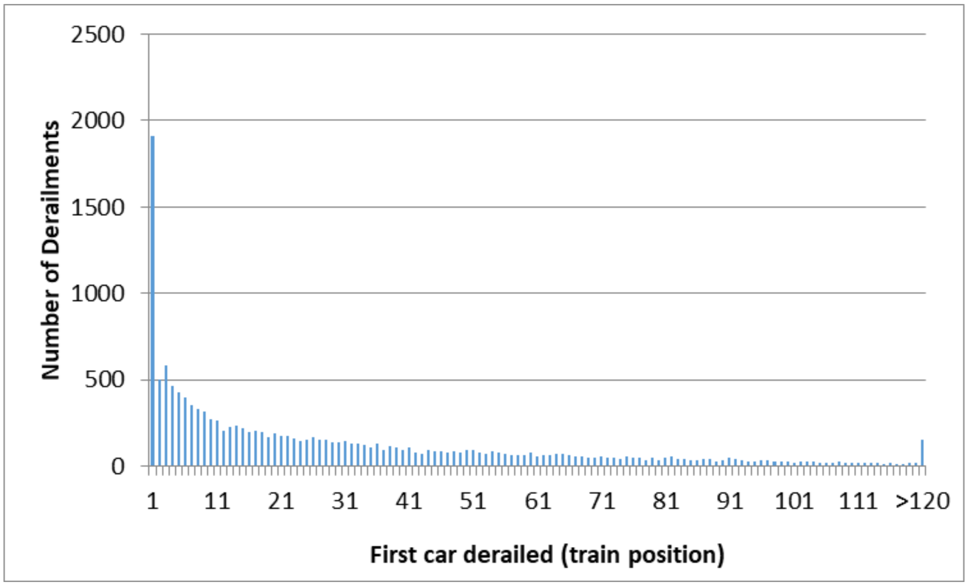

Figure 4. Frequency (count) of the first car position-in-train for mainline derailments with train speeds less than or equal to 25 mph (total count equals 14,180 derailments).

The data reveal that when a train accident results in a derailment, the first car derailed is usually the head car (position 1). In fact, for the data provided in Figure 3, the first car derailed is one of the first ten cars in nearly a third (28%) of all mainline derailments where train speeds are between 25 mph and 50 mph. Similar results are found for the percentage of derailments starting with a car in position 1-10 for the low speed case with 39% for mainline derailments where train speeds are less than 25 mph. Representative probability values of first car derailed versus position are provided in Table 8.

Table 8. Representative probability of position-in-train of first car derailed (1997-2016) given that an accident with derailment has occurred.

Statistic	Car Position in Train			
	1	11	21	31
Mainline Derailment Accident, Speed ≤ 25 mph	13.5%	1.87%	1.23%	1.02%
Mainline Derailment Accident, Speed > 25 to ≤ 50 mph	13.4%	1.20%	0.91%	0.80%

Assuming the train configuration is described by LNG DOT-113 tank cars starting at position eleven (11) and continuing until the end of the train, the probability of having a given number of LNG DOT-113 rail cars involved in the derailment was calculated for both the high speed and low speed cases. Using the average number of involved cars, and the position-in-train derailment probabilities from Figure 3 and Figure 4, the probability of having 1-11 cars (for high speed mainline movement) and 1-5 cars (for low speed mainline movement) were calculated. These probabilities are provided in Table 9.

Table 9. Probability of having 'X' number of LNG DOT-113 rail cars involved in a train accident with derailment, by train speed.

'X' Number of LNG DOT-113 Cars Involved in Train Accident with Derailment	Probability of 'X' Number of LNG DOT-113 Cars Involved in Train Accident with Derailment	
	High Speed (25 - 50 mph)	Low Speed[21] (≤ 25 mph)
1	13.4%	2.48%
2	2.17%	2.34%
3	3.06%	2.23%
4	1.54%	1.91%
5	1.60%	60.9%
6	1.40%	
7	1.49%	
8	1.23%	
9	0.943%	
10	1.40%	
11	71.8%	

3.1.3 DOT-113 LOC Probabilities

The prior sections detailed the development of accident rate and derailment probability estimates for LNG DOT-113 cars. Not every accident will lead to an LOC of LNG. The specific dynamics of an individual accident will dictate whether and to what extent an LOC may occur. This section discusses the development of LOC and release size probability estimates for the QRA model based on industry data and guidelines.

LOC probability data for LNG in DOT-113 tank cars does not exist, so general rail industry data was used and reasonable engineering assumptions were made, as necessary. Pressure tank cars and cryogenic tank cars have an extensive history of operation with corresponding accident data, and with some engineering judgement, this type of accident data was applied to shipping

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[21] It should be noted that the probability for LNG DOT-113 rail car involvement at low speeds does not equal 100%, unlike at high speeds. This is due to the average number of cars derailed equal to five (5) at low speeds; thus, first car derailment at train positions 1-6 will not result in LNG OT-113 rail car involvement.

LNG DOT-113s. A flow chart supplementing the following discussion is provided in Figure 5 at the end of this section.

The Pipeline and Hazardous Materials Safety Administration (PHMSA) maintains an online database that provides historical LOC data for rail tank cars, among other transportation vessels.[22] The database complements the FRA database in that the PHMSA database records the inventory of HAZMAT cargo released for each accident; whereas, the FRA database only identifies that an LOC has occurred. The PHMSA database was analyzed in order to estimate the LOC probabilities for the LNG DOT-113 cars. The PHMSA database provided relatively scant accident data for DOT-113 rail cars (and did not contain catastrophic release scenarios), but it did list a significant number of pressure tank car LOC accidents. Although there are differences between the DOT-113 construction and, for example, a DOT-112 pressure tank car, the analysis is likely representative of DOT-113 rail cars. Thus, pressure tank cars were used as an analog to estimate the probability of an LOC if a car was derailed.

The PHMSA database listed accident data from 1971 to the present. All rail car data was queried from 1971 to 2017, for incidents including spillage, vapor (gas) dispersion, and no release. The resulting data was then filtered for pressure tank cars only, and incidents where no tank car specification was available were excluded from the analysis. The resulting 5,542 pressure tank car incidents[23] were then sorted by amount released (units are either cubic feet (ft^3) or gallons).

The PHMSA data was grouped into four release volume ranges in order to estimate the probability of a certain leak size. The categories were no release (less than 100 gallons), small release (100 to 1,000 gallons), large release (1,000-30,000 gallons), and catastrophic release (30,000+ gallons).[24] These volumes were chosen as the PHMSA data appeared to reflect mostly 30,000+ gallon tank cars.

Representative hole sizes were chosen for each release category, in line with PHAST calculation results assuming storage at 90 psig. Small releases were modeled using a ½-inch hole while a 2-inch hole was used for large releases. A catastrophic release assumes that the tank shell has been ruptured, leading to an instantaneous spill of the entire tank contents. Catastrophic releases were thus assumed to represent the PHMSA database cases where 30,000 gallons or more of contents were spilled. The resulting release probabilities are provided in Table 10.

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[22] Accessible via hazmatonline.phmsa.dot.gov/IncidentReportsSearch/search.aspx.

[23] As of September 20, 2017.

[24] Section 3.3.3.3, Railways, page 3.13 in *Guideline for Quantitative Risk Assessment, Part Two: Transport* (Dutch Purple Book), Publication Series on Dangerous Substances, Ministerie van Verkeer en Waterstaat (2005).

Table 10. PHMSA pressure tank car incident data from 1971-2017 and equivalent release scenarios based on a sensitivity analysis of spill diameters.

Quantity Released in gallons	Incident Count	Probability	Release Scenario
≤ 100	5,297	0.955	No Release
100 < x ≤ 1,000	88	0.016	½-inch Leak
1,000 < x ≤ 30,000	142	0.026	2-inch Leak
> 30,000	15	0.003	Catastrophic

The LOC probabilities estimated here are based on data for all pressurized tank car accidents. As a comparison, Jeong developed a probabilistic puncture model for head impact to general tank cars as a function of wall thickness.[25] The author analyzed proprietary accident data collected since 1960 by the Railway Supply Institute and the Association of American Railroads (AAR). He found that a probabilistic model closely matched historical data reflecting a historical probability of approximately 1-3% for head puncture due to derailment or collision for jacketed vessels and 3-8% for non-jacketed vessels. These statistics are consistent with our analysis of the publicly available HAZMAT data from DOT as listed in Table 10 above (i.e., 4.5% total probability of LOC).

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[25] Jeong DY. Probabilistic Approach to Conditional Probability of Release of Hazardous Materials from Railroad Tank Cars During Accidents, Proceedings of IMECE2009, ASME International Mechanical Engineering Congress and Exposition, Lake Buena Vista, Florida, USA (November 13-19, 2009).

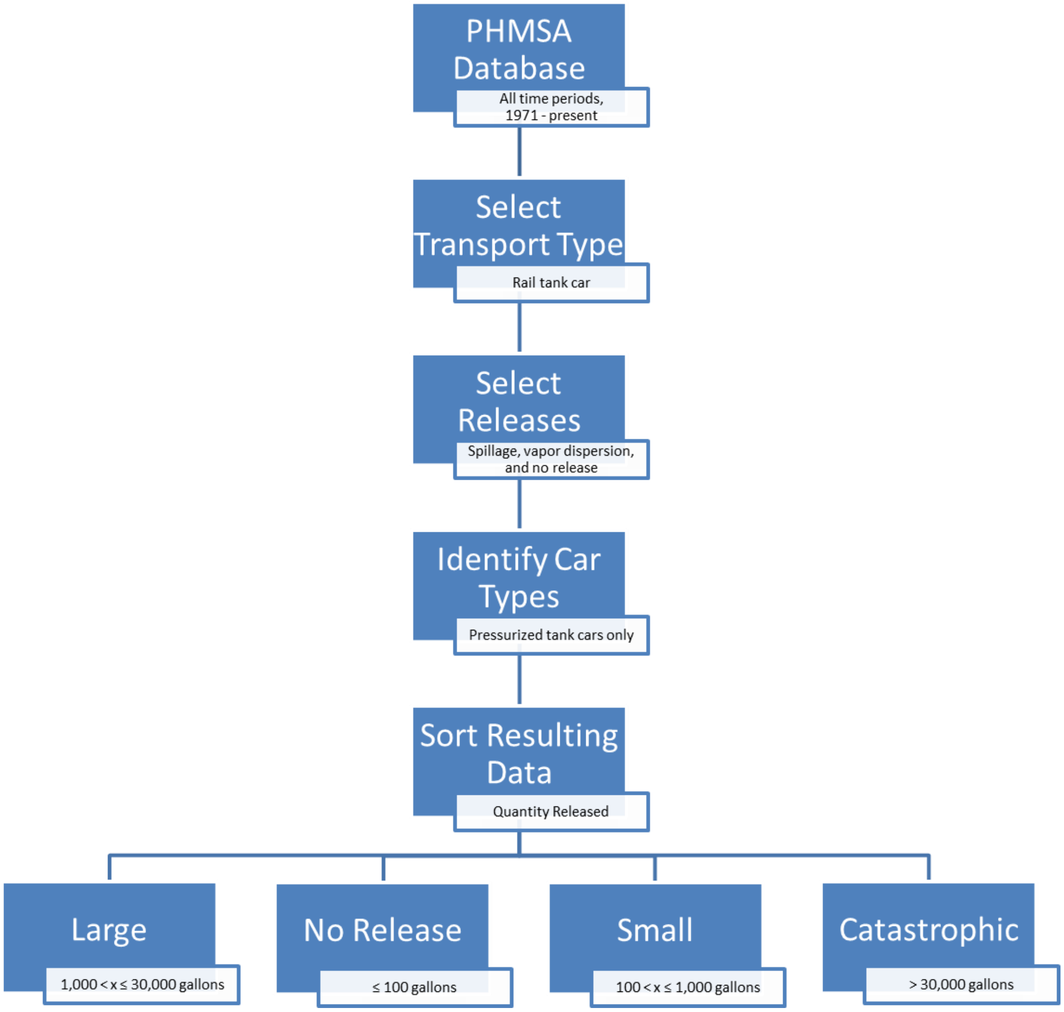

Figure 5. Flow chart describing the LNG LOC probability estimation approach.

3.1.4 Multiple LNG DOT-113 LOC Events

As the number of cars involved in an accident increases, the number of possible release scenarios grows exponentially. For example, an accident involving five cars, each with four possible outcomes, results in 4^5 (i.e. 1,024) possible combinations. PHAST Risk requires that each outcome be modeled as a single release; for example, a small release from one car combined with a large release from a second car would need to be combined into an equivalent release scenario. Within all of these combinations, several distinct outcomes are represented. As such, the combinatorial releases were grouped by discharge rates with aggregate probabilities of LOC. The outcomes were then refined by eliminating all potential LOC events with probabilities less than 1×10^{-7}; below this probability value, the risk was assumed to be insignificant.

None of the permutations were limited to only one DOT-113 for all leak scenarios. Consolidated release rates ranged from 0 to approximately 330 lb/s depending upon the case. None of the permutations led to an equivalent catastrophic release of more than three LNG DOT-113 rail cars. The consolidated releases for accidents involving two through eleven LNG DOT-113 rail cars are shown in Table 11 through Table 20.

Table 11. Consolidated release scenarios for two LNG DOT-113s.

Equivalent release (lb/s)	Probability
0	9.12×10^{-1}
3.60	3.06×10^{-2}
7.20	2.56×10^{-4}
60.4	5.05×10^{-2}
117	6.76×10^{-4}
Catastrophic Rupture (1 DOT-113)	5.98×10^{-3}
Catastrophic Rupture (2 DOT-113s)	9.00×10^{-6}

Table 12. Consolidated release scenarios for three LNG DOT-113s.

Equivalent release (lb/s)	Probability
0	8.71×10^{-1}
5.40	4.45×10^{-2}
10.8	4.10×10^{-6}
62.2	7.35×10^{-2}
148	1.99×10^{-3}
Catastrophic Rupture (1 DOT-113)	8.95×10^{-3}
Catastrophic Rupture (2 DOT-113s)	2.69×10^{-5}

Table 13. Consolidated release scenarios for four LNG DOT-113s.

Equivalent release (lb/s)	Probability
0	8.32×10^{-1}
5.40	5.71×10^{-2}
12.6	1.57×10^{-5}
64.0	9.52×10^{-2}
178	3.89×10^{-3}
Catastrophic Rupture (1 DOT-113)	1.19×10^{-2}
Catastrophic Rupture (2 DOT-113s)	5.37×10^{-5}
Catastrophic Rupture (3 DOT-113s)	1.08×10^{-7}

Table 14. Consolidated release scenarios for five LNG DOT-113s.

Equivalent release (lb/s)	Probability
0	7.94×10^{-1}
5.40	6.87×10^{-2}
14.4	3.77×10^{-5}
65.8	1.15×10^{-1}
180	6.36×10^{-3}
Catastrophic Rupture (1 DOT-113)	1.48×10^{-2}
Catastrophic Rupture (2 DOT-113s)	8.92×10^{-5}
Catastrophic Rupture (3 DOT-113s)	2.68×10^{-7}

Table 15. Consolidated release scenarios for six LNG DOT-113s.

Equivalent release (lb/s)	Probability
0	7.59×10^{-1}
5.40	7.95×10^{-2}
16.2	7.23×10^{-5}
67.6	1.35×10^{-1}
155	9.33×10^{-3}
266	6.53×10^{-6}
Catastrophic Rupture (1 DOT-113)	1.77×10^{-2}
Catastrophic Rupture (2 DOT-113s)	1.33×10^{-4}
Catastrophic Rupture (3 DOT-113s)	5.35×10^{-7}

Table 16. Consolidated release scenarios for seven LNG DOT-113s.

Equivalent release (lb/s)	Probability
0	7.24×10^{-1}
7.20	8.94×10^{-2}
19.8	2.02×10^{-6}
64.0	1.52×10^{-1}
76.6	1.64×10^{-7}
151	1.28×10^{-2}
262	1.48×10^{-5}
Catastrophic Rupture (1 DOT 113)	2.06×10^{-2}
Catastrophic Rupture (2 DOT 113s)	1.86×10^{-4}
Catastrophic Rupture (3 DOT-113s)	9.34×10^{-7}

Table 17. Consolidated release scenarios for eight LNG DOT-113s.

Equivalent release (lb/s)	Probability
0	6.92×10^{-1}
7.20	9.83×10^{-2}
21.6	3.87×10^{-6}
71.2	1.70×10^{-1}
130	1.59×10^{-2}
218	8.78×10^{-4}
293	5.80×10^{-7}
Catastrophic Rupture (1 DOT-113)	2.35×10^{-2}
Catastrophic Rupture (2 DOT 113s)	2.47×10^{-4}
Catastrophic Rupture (3 DOT-113s)	1.49×10^{-6}

Table 18. Consolidated release scenarios for nine LNG DOT-113s.

Equivalent release (lb/s)	Probability
0	6.61×10^{-1}
7.20	1.07×10^{-1}
18.0	6.67×10^{-6}
67.6	1.85×10^{-1}
160	2.10×10^{-2}
207	4.58×10^{-5}
325	5.32×10^{-6}
Catastrophic Rupture (1 DOT-113)	2.64×10^{-2}
Catastrophic Rupture (2 DOT-113s)	3.17×10^{-4}
Catastrophic Rupture (3 DOT-113s)	2.23×10^{-6}

Table 19. Consolidated release scenarios for ten LNG DOT-113s.

Equivalent release (lb/s)	Probability
0	6.31×10^{-1}
7.20	1.14×10^{-1}
18.0	1.06×10^{-5}
65.8	2.00×10^{-1}
134	2.40×10^{-2}
221	1.80×10^{-3}
330	2.64×10^{-6}
Catastrophic Rupture (1 DOT-113)	2.92×10^{-2}
Catastrophic Rupture (2 DOT-113s)	3.95×10^{-4}
Catastrophic Rupture (3 DOT-113s)	3.17×10^{-6}

Table 20. Consolidated release scenarios for eleven LNG DOT-113s.

Equivalent release (lb/s)	Probability
0	6.03×10^{-1}
7.20	1.21×10^{-1}
18.0	1.61×10^{-5}
67.6	2.13×10^{-1}
134	2.85×10^{-2}
221	2.41×10^{-3}
330	4.72×10^{-6}
Catastrophic Rupture (1 DOT-113)	3.20×10^{-2}
Catastrophic Rupture (2 DOT-113s)	4.82×10^{-4}
Catastrophic Rupture (3 DOT-113s)	4.35×10^{-6}

3.2 Flammable Cloud Formation

The only operation considered for the LNG DOT-113 tank car in this assessment is the main line movement. The DOT-113s are assumed to have an LNG capacity of 30,000 gallons, and it is expected to be handled at its boiling point temperature (i.e., saturation temperature of -203°F / -142°C) at the design pressure of 90.0 psig. The ½-inch and 2-inch hole size scenarios conservatively assumed a constant leak source at these conditions; it was assumed that the LNG was released at this same pressure and temperature for the catastrophic release scenario. For calculation of vaporization rates due to the evaporation of spilled LNG, it was assumed that the LNG was spilled on dry soil. The release elevation used in the analysis was 6-ft, and all releases were assumed to be directed horizontally to conservatively maximize the flammable vapor dispersion distance.

The release conditions, LNG vaporization, cloud formation and dispersion, and flammable cloud envelope as a function of time were calculated in PHAST Risk v6.7. PHAST Risk is a commercial software package developed and distributed by Det Norske Veritas (DNV). PHAST Risk combines a phenomenological release and consequence analysis model with a risk analysis sub-model to evaluate spills, sprays, and gas dispersions and the resulting toxic, fire, and explosion consequences on populations.

PHAST is widely used for the calculation of hazard distances from the release of several hazardous substances, including LNG. PHAST is approved by the U.S. Pipeline and Hazardous Materials Safety Administration (PHMSA) for evaluating LNG release exclusion zones. The PHAST code uses the Unified Dispersion Model (UDM) as an integral calculation model to estimate the dispersion following a pressurized release or an unpressurised release. It consists of the following linked modules (as shown in Figure 6):

- Near-field jet dispersion
- Non-equilibrium droplet evaporation and rainout, touchdown
- Pool spread and vaporization
- Heavy gas dispersion
- Far field passive dispersion

The UDM allows for continuous, instantaneous, constant finite-duration and general time-varying releases. The UDM also allows for possible plume lift-off if a grounded plume becomes buoyant. The UDM has been validated extensively with experimental data and is the subject of several peer-reviewed scientific papers.[26] The PHAST-UDM has also been approved by PHMSA for analyzing LNG vapor dispersion exclusion zones.[27]

PHAST model calculations assume that the terrain is completely flat and do not account for any obstructions (either natural or nearby equipment) on the dispersion distance of flammable clouds. In many cases, this assumption produces a conservative overestimate of the distance to hazardous outcomes.

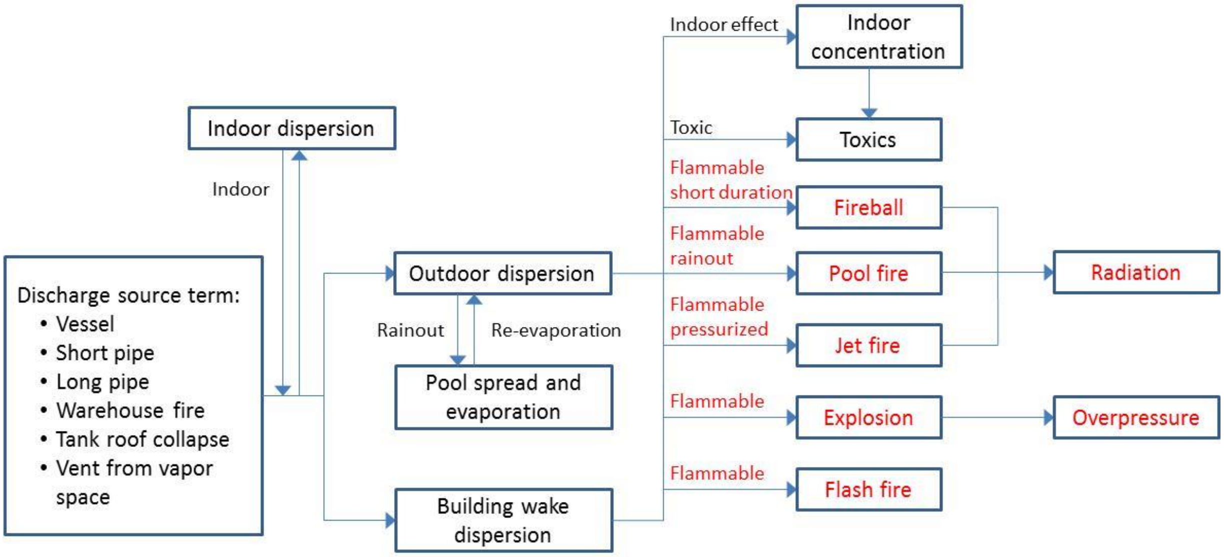

Figure 6. Block diagram for PHAST.

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[26] Witlox, H.W.M. and Holt, A., 1999, A unified model for jet, heavy and passive dispersion including droplet rainout and re-evaporation, International Conference and Workshop on Modeling the Consequences of Accidental Releases of Hazardous Materials, CCPS, San Francisco, California, September 28-October 1, pages 315–344.

[27] PHMSA Docket No. 2011-0075, October 11, 2011.

3.3 Ignition of a Flammable Cloud

Given a release of LNG and the formation of a flammable cloud, the hazardous outcomes analyzed in the QRA only occur if there is ignition of the flammable mixture. The timing of the ignition affects the consequence outcome because the flammable cloud stops growing after ignition since the flammable vapor will be burned. For example, immediate ignition of the release may result in a pool fire or jet fire (or both); delayed ignition may result in a pool fire, flash fire, or explosion. For each scenario modeled, PHAST Risk calculates the outcome due to both immediate ignition and delayed ignition for the range of outcomes in the event tree. The immediate and delayed ignition probabilities in PHAST Risk are consistent with the guidelines published in the Dutch Purple Book.[28,29]

Exponent applied the default PHAST Risk ignition probability values for two release types:

- “Stationary” facility ignition probabilities were assigned for lifting operation incidents.
- “Tank wagon” (i.e., rail tank car) ignition probabilities were assigned for the train movement incidents.

An overview of PHAST Risk’s probability of ignition model is provided in the following sections.

3.3.1 Probability of Immediate Ignition

Methane is defined as a low reactivity material in the software, and the probability of immediate ignition has a fixed value depending upon the hole size. PHAST Risk also considers a catastrophic instantaneous release of the entire contents of the vessel and calls this an “instantaneous” release. The term “tank wagon” refers to rail tank cars and was used to represent LNG DOT-113s during train movement here. The “tank wagon” immediate ignition probability only depends on whether the release is continuous or instantaneous; the rate of release is not considered. Table 31 lists the probability of immediate ignition for the scenarios identified in the QRA (see also the flammable event trees in Figure 7 and Figure 8).

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[28] PHAST Risk Technical Documentation, “MPACT Theory,” DNV Software, page 103 (2010).

[29] Chapter 4.7, Ignition, in *Guideline for Quantitative Risk Assessment* (Dutch Purple Book), Publication Series on Dangerous Substances, Ministerie van Verkeer en Waterstaat (2005).

Table 21. Probability of immediate ignition for methane in PHAST Risk

Hole Size	Rail Tank Car
0.5-inch	0.1
2-inch	0.1
Instantaneous	0.8

3.3.2 Probability of Delayed Ignition

The probability of delayed ignition is dependent upon many characteristics of the release scenario, including the growth of an un-ignited vapor cloud with time and the presence of potential ignition sources at some distance from the point of release. Thus, the probability of delayed ignition is not a fixed value; it is calculated as a function of space and time for the duration of the event. The model domain space is split into grid cells, and the size of the cells is an integer value dependent on the size of the model domain. PHAST Risk performs calculations for each grid cell and sums the probability of ignition for all cells at a given time step as a function of the flammable cloud growth and passage through the model domain. The domain is the maximum spatial extent of the consequence (e.g., maximum flammable cloud size), and PHAST Risk uses up to 40,000 grid cells for analyzing the domain.

For each step forward in time after the start of the release, every grid cell that overlaps with a portion of the flammable cloud will have a probability of delayed ignition. The delayed ignition probability for a given grid cell is calculated from the equation,

$$P_{x,y,t} = f_{x,y}(1 - e^{-n\omega_{x,t}t})$$

where $P_{x,y,t}$ is the probability of delayed ignition in the grid cell located at (x,y). The variable $f_{x,y}$ is the proportion of time that the ignition source is present and active in the grid cell located at (x,y), $\omega_{x,y}$ is the ignition effectiveness factor for that grid cell, n is the number of people in the grid cell, and t is the time step. No fixed location ignition sources were defined in the QRA analysis presented here (e.g., a stationary flare), thus the PHAST Risk delayed ignition probability model considers only the potential for ignition due to the surrounding population. The default PHAST Risk ω for ignition due to population used in this analysis was 1.68×10^{-4}/person (for outdoor populations only). Thus, the ignition effectiveness factor, ω, in the QRA is dependent only on the population specified in each grid cell in the domain. The probability of delayed ignition in a given grid cell at a given time step increases with increasing population (holding all other variables constant). Since the risk within a given grid cell is directly related to the probability of ignition through all time steps, the risk will increase with an increase in the probability of ignition.

3.4 Flammable Effects on a Population

The flammable effects resulting from a release of LNG include pool fires, jet fires, flash fires, and fireballs. The probability that an exposed population will suffer a fatality due to exposure to a flammable effect depends on the extent of exposure and protection of the population (indoor versus outdoor). For the IR calculations, PHAST Risk assumes that the entire population is outdoors. For the SR calculations, the standard model assumes that 90% of the population is indoors and 10% is outdoors. All calculations assume that people are at ground level, so the ground level effect zones are used in calculating consequence outcomes.

The flammable effects and fatality consequences are calculated in PHAST Risk utilizing a grid cell system to calculate fatalities in effect zones, and the probability of fatality as a function of distance is calculated. As previously described, the model domain is split into grid cells, and the size of the cells is an integer value dependent on the size of the model domain. The effect zones for fireballs, jet fires, and pool fires are modeled as ellipses. The shape of the vapor cloud determined from the dispersion calculations defines the shape of the flash fire. For grid cells where the flammable effect only overlaps a portion of the cell, the fraction of overlap is considered in calculating the fatality probability.

The flammable effect in a grid is then compared to the populations in that grid to determine the probability and number of expected fatalities. For the IR calculations, the model only considers whether a person is located in a grid cell, which is always assumed to be yes. To obtain the SR outputs, the flammable effect consequences are integrated by the number of people present in the grid cell (defined by the population density and size of the grid cell) to obtain the number of expected fatalities.

The flammable effect consequence methods used in PHAST Risk are consistent with the guidelines published in the Dutch Green Book[30] (and applied to QRA in the Dutch Purple Book[31]).[32] The Probit Method, which is dependent on radiation level and exposure time, is used to calculate the probability of fatality for flammable effects on exposed populations for fireball, pool fire, and jet fire effects. This method is applied to each grid cell independently and then the cumulative consequence outcome for a specific flammable effect is obtained by summing all the grid cells.

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[30] Chapter 1, Damage Caused by Heat Radiation, in *Methods for the Determination of Possible Damage* (Dutch Green Book), Publication Series on Dangerous Substances, Ministerie van Verkeer en Waterstaat (1992).

[31] Chapter 5, Modeling Exposure and Damage, in *Guideline for Quantitative Risk Assessment* (Dutch Purple Book), Publication Series on Dangerous Substances, Ministerie van Verkeer en Waterstaat (2005).

[32] PHAST Risk Technical Documentation, “MPACT Theory,” DNV Software, pages 66-94 (2010).

The consequence outcomes for the classes of flammable effects are summarized (the flame envelope is defined as the area between the lower flammable limit, LFL, and upper flammable limit, UFL):

- Fireball, pool fire, jet fire—all persons, indoor and outdoor, within the flame envelope are considered fatalities. All persons, indoor and outdoor, exposed to radiation levels exceeding 11,000 BTU/hr/ft^2 (35 kW/m^2) are considered fatalities. For smaller radiation levels, the Probit method is utilized to calculate the probability of fatality.
- Flash fire—all persons, indoor and outdoor, within the flame envelope are considered fatalities. All persons, indoor and outdoor, outside of the flame envelope are not considered fatalities.
- Explosion—all persons, indoor and outdoor, exposed to overpressures exceeding 4.35 psig (0.3 barg) are considered fatalities. All indoors persons exposed to overpressures exceeding 1.45 psig (0.1 barg) are considered have a 2.5% probability of fatality. All other exposures are not considered fatalities. The TNT-equivalency explosion method (efficiency of 10%) is used to calculate the overpressure profile for explosion.

3.4.1.1 Representative Hazard Distances

Representative hazard distances for small (0.5-inch leak), large (2-inch leak), and catastrophic rupture of the DOT-113 tank cars are provided in Table 22. The releases are considered to occur at the MAWP of the LNG DOT-113 (90 psig) and saturation temperature for methane (-203 °F), at an elevation of 6-ft. The release distances were calculated in PHAST v6.7 using the hazard thresholds described above.

Table 22. Representative hazard distances for LNG releases from DOT-113 tank cars.

Release Scenario	Flash Fire Hazard Distance (ft)	Explosion Overpressure Hazard Distance (ft)	Jet Fire or Fireball Hazard Distance (ft)
Hazard Threshold	**Lower Flammability Limit (LFL)**	**4.35 psig (0.3 barg)**	**11,100 BTU/hr-ft^{2v} (35 kW/m^2)**
0.5-inch	52.4	46.6	78.7
2-inch	293	339	275
Catastrophic Rupture	482	757	356

The hazard distances presented here represent the worst-case potential outcome, assuming the flammable clouds are allowed to fully develop (i.e. ignition occurs once the flammable clouds reach their maximum extent). These distances do not reflect the risk from the releases as the hazard outcome probabilities are not considered. These consequences are unlikely to occur in the event of a release, and these hazard distances should not be construed as potential risk zones, but rather maximum potential events irrespective of likelihood.

3.4.2 Flammable Effects Event Trees

The flammable effects resulting from a release of LNG include pool fires, jet fires, flash fires, and fireball. The likelihood of each effect and the consequence outcome are affected by many parameters in the model. The probability of any of these outcomes occurring (or no ignition at all) is complex and is dealt with in PHAST by use of event trees. The probabilities of an individual consequence for a given release depends on whether the release is instantaneous (e.g., catastrophic scenarios) or continuous (e.g., the other scenarios considered), the presence of liquid rainout, subsequent pool vaporization, the presence of a persistent liquid pool, and the dispersion behavior of the flammable vapors.

A majority of the LNG releases considered here are continuous and will have some significant fraction of LNG that flashes immediately upon release. The event tree used in PHAST to represent the probabilistic outcomes for these continuous releases without liquid rainout is provided in Figure 7. The event tree used in PHAST for the catastrophic rupture events is provided in Figure 8.

Similar event trees exist for a continuous release with no rainout, an instantaneous release with no rainout, and an instantaneous release with rainout. The structure of the event trees is consistent with guidance in the Dutch Purple Book.[33] Each branch of these event trees corresponds to a probability of occurrence for that branch, and the sum of all branches for a given step (i.e., branches aligned vertically) sums to unity. The probabilities used in PHAST Risk are consistent with the values provided in the Dutch Purple Book.[34] For the 'No-immediate ignition' branch of the example event tree provided in Figure 7, the probability of delayed ignition ($P_{x,y,t}$) is calculated for each time step for each cell in the model domain (see Section 3.3.2). The outcomes in the delayed ignition branch have a 60% probability of resulting in a flash fire and a 40% probability of resulting in an explosion.

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[33] *Guideline for Quantitative Risk Assessment* (Dutch Purple Book), Publication Series on Dangerous Substances, Ministerie van Verkeer en Waterstaat (2005).

[34] PHAST Risk Technical Documentation, "MPACT Theory," DNV Software, page 128 (2010).

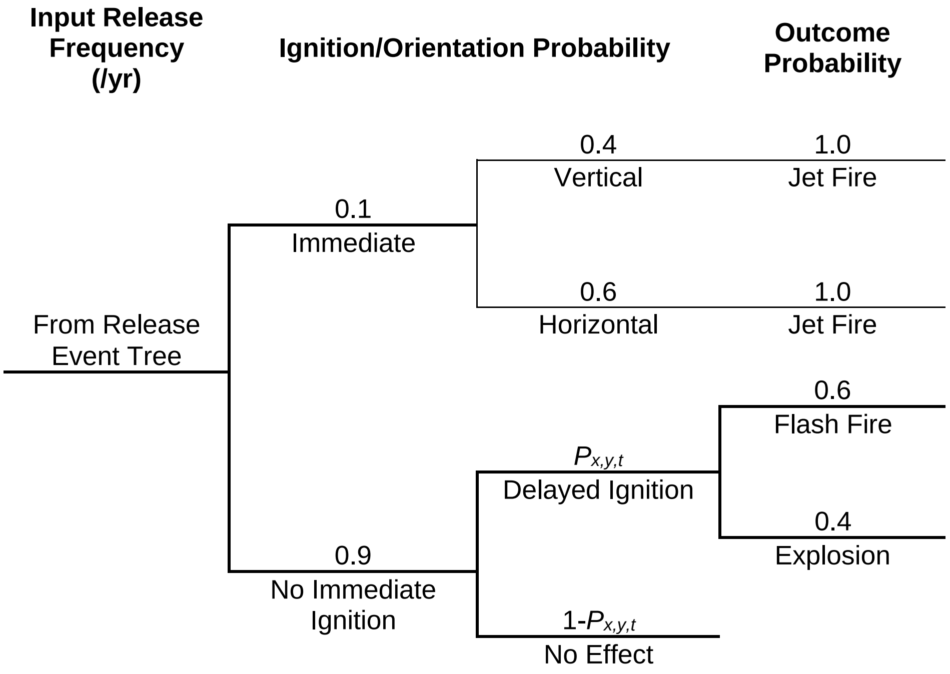

Figure 7. PHAST Risk consequence event trees for a continuous release without liquid rainout; for example, applied to the 0.5-inch leak and 2-inch leak along mainline movement.

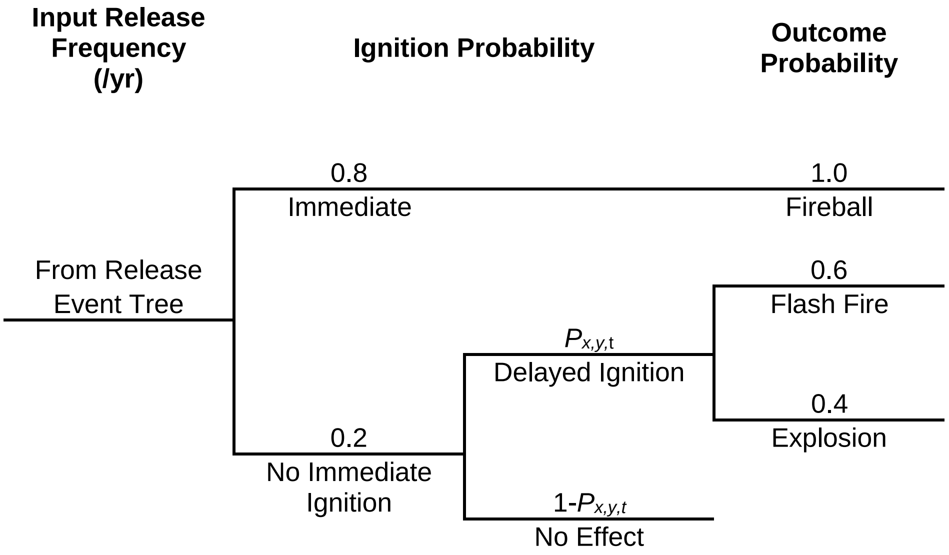

Figure 8. PHAST Risk consequence event trees for an instantaneous release without liquid rainout; for example. applied to the catastrophic rupture along mainline movement.

4 Release Scenario Frequencies

Several accidental release scenarios were analyzed using the PHAST Risk software for the LNG DOT-113 tank car operations. The PHAST Risk software requires definition of the release sizes (e.g., no release, small, large, and catastrophic as defined earlier), release conditions, and the LOC frequency for each size of hole for each release scenario.

Event trees representing the two mainline train speeds are provided in Appendix B. The following tables summarize the release rates and associated release frequencies for combinations of one to eleven DOT-113s along mainline train movement at the two train speeds, low speed and high speed. The release frequencies are a function of the length of the route; therefore, each route has a distinct table of release frequencies. “Release Frequency” is the product of the “Initiating Event Frequency,” “Derailment Probability,” “Multiple Accident Probability,” and “Release Probability.”

Table 23. Event frequencies for LNG DOT-113 mainline movement release scenarios along the example route, with train speeds greater than 25 mph and up to 50 mph.

Release rate (lb/s)	Release Frequency (/year)
1 DOT-113 Involved	
0	6.03×10^{-5}
3.60	1.01×10^{-6}
58.6	1.64×10^{-6}
CR 1 DOT-113	1.89×10^{-7}
2 DOT-113s Involved	
0	9.31×10^{-6}
3.60	3.12×10^{-7}
7.20	2.61×10^{-9}
60.4	5.16×10^{-7}
117	6.90×10^{-9}
CR 1 DOT-113	6.10×10^{-8}
CR 2 DOT-113	9.18×10^{-11}
3 DOT-113s Involved	
0	1.25×10^{-5}
5.40	6.40×10^{-7}
10.8	5.89×10^{-11}
62.2	1.06×10^{-6}
148	2.86×10^{-8}
CR 1 DOT-113	1.29×10^{-7}
CR 2 DOT-113	3.86×10^{-10}
4 DOT-113s Involved	
0	6.03×10^{-6}
5.40	4.14×10^{-7}
12.6	1.14×10^{-10}
64.0	6.90×10^{-7}
178	2.82×10^{-8}
CR 1 DOT-113	8.63×10^{-8}
CR 2 DOT-113	3.89×10^{-10}
CR 3 DOT-113	7.83×10^{-13}
5 DOT-113s Involved	
0	5.97×10^{-6}
5.40	5.17×10^{-7}
14.4	2.84×10^{-10}
65.8	8.68×10^{-7}
180	4.78×10^{-8}
CR 1 DOT-113	1.11×10^{-7}
CR 2 DOT-113	6.71×10^{-10}
CR 3 DOT-113	2.01×10^{-12}
6 DOT-113s Involved	
0	4.99×10^{-6}
5.4	5.23×10^{-7}
16.2	4.76×10^{-10}
67.6	8.86×10^{-7}
155	6.14×10^{-8}
266	4.30×10^{-11}
CR 1 DOT-113	1.16×10^{-7}
CR 2 DOT-113	8.75×10^{-10}
CR 3 DOT-113	3.52×10^{-12}
7 DOT-113s Involved	
0	5.05×10^{-6}
7.20	6.24×10^{-7}
19.8	1.41×10^{-11}
64.0	1.06×10^{-6}
76.6	1.15×10^{-12}
151	8.97×10^{-8}
262	1.04×10^{-10}
CR 1 DOT-113	1.44×10^{-7}
CR 2 DOT-113	1.30×10^{-9}
CR 3 DOT-113	6.52×10^{-12}
8 DOT-113s Involved	
0	3.99×10^{-6}
7.20	5.68×10^{-7}
21.6	2.23×10^{-11}
71.2	9.79×10^{-7}
130	9.18×10^{-8}
218	5.07×10^{-9}
293	3.35×10^{-12}
CR 1 DOT-113	1.36×10^{-7}
CR 2 DOT-113	1.43×10^{-9}
CR 3 DOT-113	8.60×10^{-12}
9 DOT-113s Involved	
0	2.93×10^{-6}
7.20	4.72×10^{-7}
18.0	2.96×10^{-11}
67.6	8.20×10^{-7}
160	9.32×10^{-8}
207	2.03×10^{-10}
325	2.36×10^{-11}
CR 1 DOT-113	1.17×10^{-7}
CR 2 DOT-113	1.40×10^{-9}
CR 3 DOT-113	9.88×10^{-12}
10 DOT-113s Involved	
0	4.15×10^{-6}
7.20	7.52×10^{-7}
18.0	6.98×10^{-11}
65.8	1.31×10^{-6}
134	1.58×10^{-7}
221.2857143	1.18×10^{-8}
329.8333333	1.74×10^{-11}
CR 1 DOT-113	1.92×10^{-7}
CR 2 DOT-113	2.60×10^{-9}
CR 3 DOT-113	2.09×10^{-11}
11 DOT-113s Involved	
0	2.03×10^{-4}
7.20	4.07×10^{-5}
18.0	5.42×10^{-9}
67.6	7.17×10^{-5}
134	9.61×10^{-6}
221	8.14×10^{-7}
330	1.59×10^{-9}
CR 1 DOT-113	1.08×10^{-5}
CR 2 DOT-113	1.63×10^{-7}
CR 3 DOT-113	1.47×10^{-9}

Table 24. Event frequencies for LNG DOT-113 mainline movement release scenarios along the example route, with train speeds up to 25 mph.

Release rate (lb/s)	Release Frequency (/year)
1 DOT-113 Involved	
0	1.34×10^{-5}
3.60	2.24×10^{-7}
58.6	3.64×10^{-7}
CR 1 DOT-113	4.20×10^{-8}
2 DOT-113s Involved	
0	1.21×10^{-5}
3.60	4.05×10^{-7}
7.20	3.39×10^{-9}
60.4	6.69×10^{-7}
117	8.94×10^{-9}
CR 1 DOT-113	7.91×10^{-8}
CR 2 DOT-113	1.19×10^{-10}
3 DOT-113s Involved	
0	1.10×10^{-5}
5.40	5.61×10^{-7}
10.8	5.16×10^{-11}
62.2	9.26×10^{-7}
148	2.50×10^{-8}
CR 1 DOT-113	1.13×10^{-7}
CR 2 DOT-113	3.39×10^{-10}
4 DOT-113s Involved	
0	8.99×10^{-6}
5.40	6.17×10^{-7}
12.6	1.69×10^{-10}
64.0	1.03×10^{-6}
178	4.20×10^{-8}
CR 1 DOT-113	1.29×10^{-7}
CR 2 DOT-113	5.80×10^{-10}
CR 3 DOT-113	1.17×10^{-12}
5 DOT-113s Involved	
0	2.73×10^{-4}
5.40	2.36×10^{-5}
14.4	1.30×10^{-8}
65.8	3.97×10^{-5}
180	2.19×10^{-6}
CR 1 DOT-113	5.09×10^{-6}
CR 2 DOT-113	3.07×10^{-8}
CR 3 DOT-113	9.22×10^{-11}

5 Potentially Affected Populations

The population density along the mainline rail route directly affects the risk; thus, an example route with varying population density was considered in this analysis.

The example mainline route consists of 227 miles of mainline track. The mainline track was evaluated as 227 one-mile long segments to characterize the population density per mile along the example route. The maximum population density was approximated to be 20,000 people/mile^2. Thus, a range of population densities from 500 people/mile^2 to 20,000 people/mile^2 were explored at both high and low train speeds to analyze the risk along the route.

The range of population densities included the following:

- 20,000 people/mile^2
- 17,500 people/mile^2
- 15,000 people/mile^2
- 13,000 people/mile^2
- 11,000 people/mile^2
- 9,000 people/mile^2
- 7,000 people/mile^2
- 5,000 people/mile^2
- 4,000 people/mile^2
- 3,000 people/mile^2
- 2,000 people/mile^2
- 1,000 people/mile^2
- 500 people/mile^2

6 Weather and Terrain

The ambient air temperature and ground temperature of the route were conservatively assumed to be the annual average temperature for the Northeastern United States, specifically eastern Pennsylvania, which is 53°F (11.6°C). This ambient temperature was used for all calculations. Higher or lower temperatures are expected to impact the release consequence calculations slightly. The selection of a single temperature equal to the average annual temperature for the region is consistent with 49 CFR § 193 guidance for conducting vapor dispersion analyses of LNG releases at LNG terminal facilities.[35]

The wind speed was assumed to be constant at 4.5 mph (2 m/s) and was assumed to occur with equal likelihood in any direction. Based on experience with dense cloud dispersion, lower wind speeds typically result in the largest impact areas. A Pasquill-Gifford stability class of F was assigned for all calculations, and this value is expected to provide conservative (i.e. larger) hazard impact areas. Additionally, a wind speed of 4.5 mph (2 m/s) and Pasquill-Gifford stability class F are consistent with 49 CFR § 193 guidance for conducting vapor dispersion analyses of LNG releases. The terrain was assumed to have a surface roughness factor consistent with the same guidance (0.03 m high).

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[35] 49 CFR § 193.2059 – Flammable vapor-gas dispersion protection.

7 Results

Based on the forgoing discussion of the QRA assumptions, inputs, and calculations, the risk was calculated for the example route. The risk results are presented in the form of distance to Individual Risk thresholds, the Societal Risk integral, and Societal Risk as F-N curves for along the rail route. For the proposed mainline route, the risk results varied with population density along the railroad. The underlying accident likelihoods and release scenarios are independent of the route demographics; thus, the calculated shipping risk is directly related to the route length and population along the route. The risk is presented for a sequence of LNG DOT-113 cars shipped along the mainline at low speed and at high speed.

The risk profiles along the single mile-long section of the routes are discussed in the following sections. Although computationally efficient, examining the risk along only a single one-mile long section of route does not represent the entire risk for the proposed transport route. The total societal risk for the proposed transport routes is presented in Section 7.2.

7.1 LNG DOT-113 Shipping Risk

The LNG DOT-113 shipping risk was analyzed with a train configuration containing a sequence of LNG DOT-113 cars where the first LNG DOT-113 is at car position eleven. This configuration leads to a probability of multiple car derailment that maximizes the chances of up to eleven cars being involved in a LOC event. Thus, this configuration provides a conservative case for risk.

The FN curves were calculated as a function of population density for one mile long sections of track. The maximum IR and SR are also influenced by the magnitude of the potentially affected population within each one mile section. The maximum population density along any route was 20,000 people per square mile. This population density will therefore correlate to the highest risk for train movement anywhere along the mainline.

7.1.1 Train at Low Speeds

A summary of the baseline risk metrics for the LNG DOT-113 mainline movement at train speeds less than or equal to 25 mph case is provided in Table 25. The SR integral is the area under the FN curves presented in Figure 9.

Table 25. Mainline train speeds up to 25 mph - summary of the risk metrics for LNG DOT-113 car train movements for different population densities.

Population density (people/mile^2)	SR Integral (total risk, yr^{-1})	Maximum IR (yr^{-1})	Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)
500	3.61×10^{-5}	9.47×10^{-7}	N/A	N/A	455
1,000	7.56×10^{-5}	9.59×10^{-7}	N/A	N/A	460
2,000	1.64×10^{-4}	9.81×10^{-7}	N/A	N/A	462
3,000	2.64×10^{-4}	1.00×10^{-6}	N/A	1	465
4,000	3.74×10^{-4}	1.02×10^{-6}	N/A	65	470
5,000	4.93×10^{-4}	1.04×10^{-6}	N/A	92	475
7,000	7.57×10^{-4}	1.08×10^{-6}	N/A	115	485
9,000	1.05×10^{-3}	1.11×10^{-6}	N/A	145	495
11,000	1.36×10^{-3}	1.14×10^{-6}	N/A	160	500
13,000	1.70×10^{-3}	1.17×10^{-6}	N/A	174	505
15,000	5.49×10^{-3}	1.19×10^{-6}	N/A	175	507
17,500	2.49×10^{-3}	1.22×10^{-6}	N/A	185	510
20,000	2.96×10^{-3}	1.24×10^{-6}	N/A	195	512

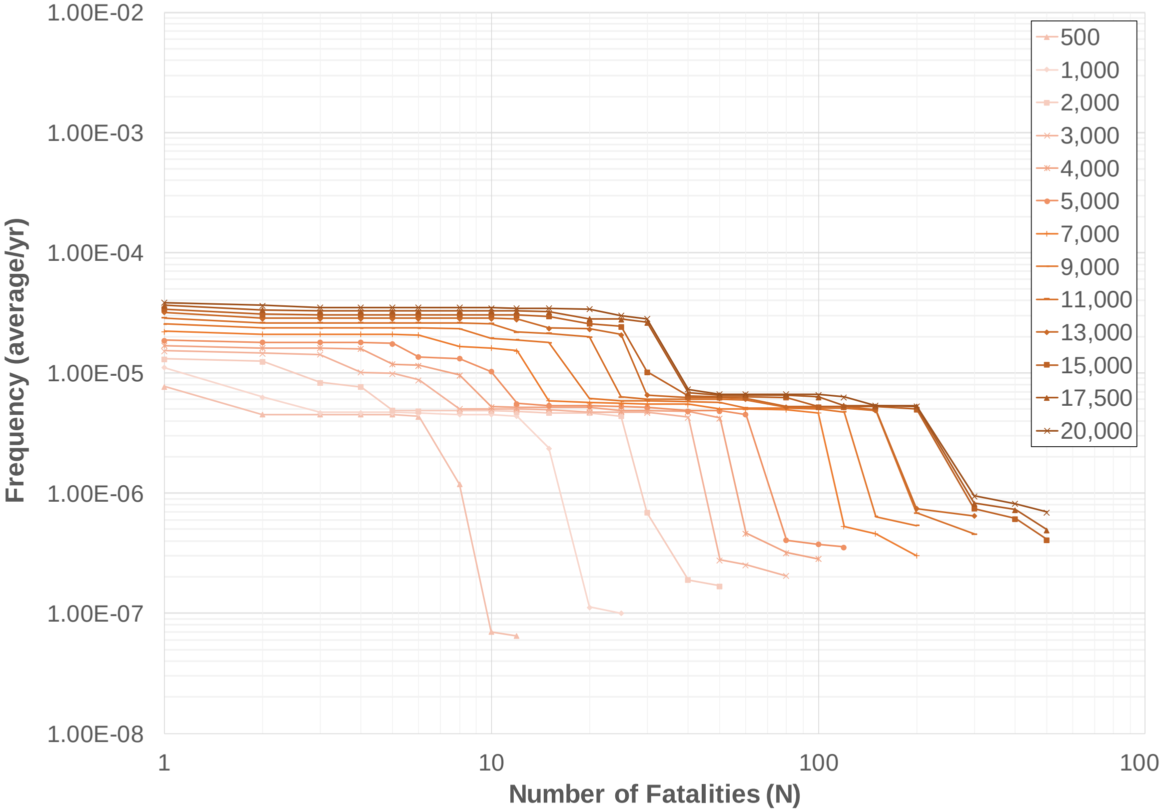

Figure 9. FN curves for the mainline train movement with train speeds up to 25 mph along different population densities (from 500 up to 20,000 people/mile^2) for one-mile section of the mainline. Note that these FN curves are only for a one-mile section of mainline with the corresponding population density.

7.1.2 Train Speeds greater than 25 mph and up to 50 mph

A summary of the baseline risk metrics for the LNG mainline movement at train speeds greater than 25 mph and up to 50 mph is provided in Table 26.

Table 26. Mainline train speeds greater than 25 mph and up to 50 mph - summary of the risk metrics for LNG DOT-113 car train movements.

Population density (people/mile^2)	SR Integral (total risk, yr^{-1})	Maximum IR (yr^{-1})	Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)
500	8.15×10^{-5}	2.11×10^{-6}	N/A	382	569
1,000	1.71×10^{-4}	2.14×10^{-6}	N/A	387	573
2,000	3.69×10^{-4}	2.19×10^{-6}	N/A	395	580
3,000	5.94×10^{-4}	2.25×10^{-6}	N/A	400	583
4,000	8.42×10^{-4}	2.29×10^{-6}	N/A	403	585
5,000	1.11×10^{-3}	2.34×10^{-6}	N/A	407	588
7,000	1.70×10^{-3}	2.43×10^{-6}	N/A	417	600
9,000	2.36×10^{-3}	2.50×10^{-6}	N/A	425	608
11,000	3.06×10^{-3}	2.57×10^{-6}	N/A	430	615
13,000	3.81×10^{-3}	2.64×10^{-6}	N/A	434	618
15,000	4.59×10^{-3}	2.70×10^{-6}	N/A	438	625
17,500	5.60×10^{-3}	2.76×10^{-6}	N/A	428	628
20,000	6.63×10^{-3}	2.82×10^{-6}	N/A	448	632

The corresponding FN curve for the mainline track movement at train speeds greater than 25 mph and up to 50 mph is provided in Figure 10.

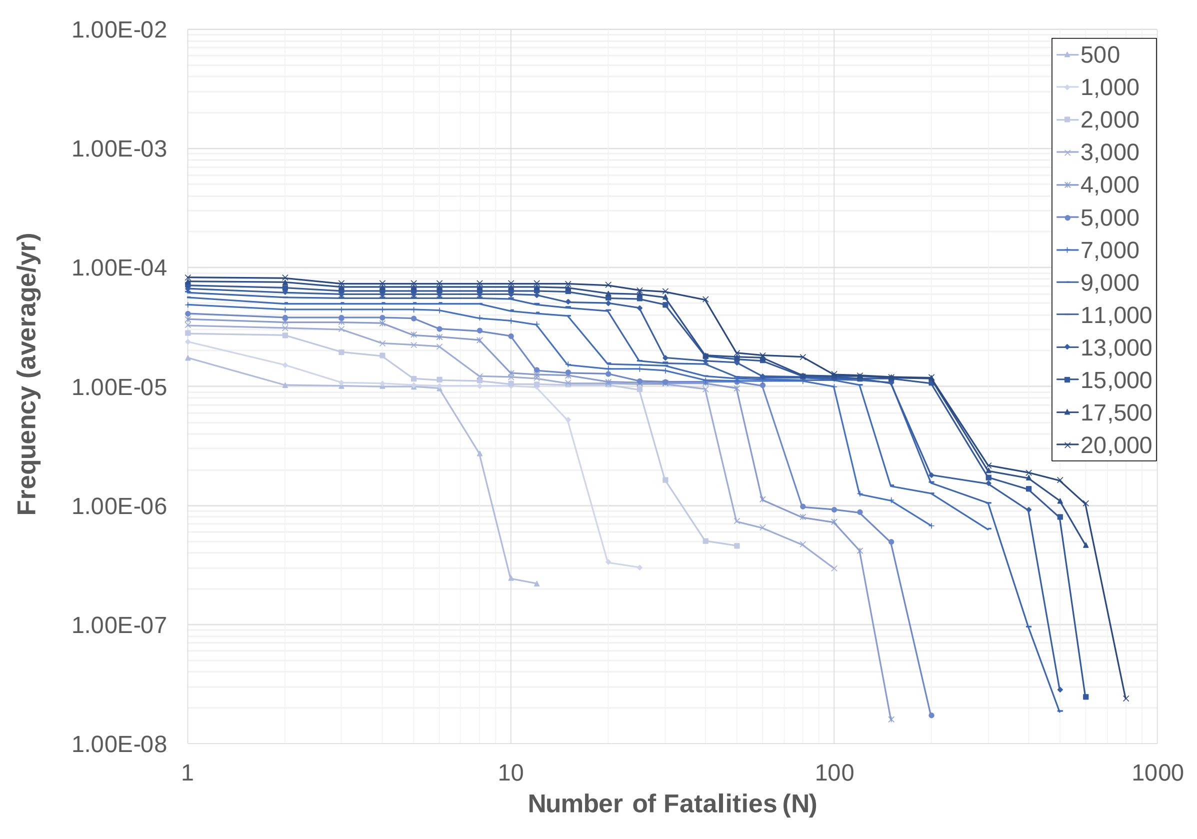

Figure 10. FN curves for the mainline train movement with train speeds greater than 25 mph up to 50 mph along different population densities (from 500 up to 20,000 people/mile^2) for one-mile section of the mainline. Note that these FN curves are only for a one-mile section of mainline with the corresponding population density.

7.2 Aggregate Societal Risk

The aggregate societal risk represents the total societal risk profile posed by transport along the entire route. For relatively long routes, the computational time and model development can be prohibitive; thus, an efficient and computationally manageable approach is desired. In this section, we describe the approach and results for determining the aggregate risk along the route by:

(1) Sub-dividing the route into smaller sections using representative population densities,

(2) Calculating the societal risk for each section, and

(3) Summing the risk for the sections.

As described earlier, the ETS example route is subdivided into 227 1-mile sections. These sections along each route were then grouped into population ranges to conservatively represent the number of 1-mile sections for a given population density along a given route, as shown in Table 27.

Table 27. Population range groupings for 1-mile sections along the route.

Population Density Range (people/mile^2)	Population Density used in Calculation (people/mile^2)	Number of 1-mile Segments along the Route
17,500 < x ≤ 20,000	20,000	1
15,000 < x ≤ 17,500	17,500	2
13,000 < x ≤ 15,000	15,000	2
11,000 < x ≤ 13,000	13,000	0
9,000 < x ≤ 11,000	11,000	2
7,000 < x ≤ 9,000	9,000	4
5,000 < x ≤ 7,000	7,000	11
4,000 < x ≤ 5,000	5,000	10
3,000 < x ≤ 4,000	4,000	7
2,000 < x ≤ 3,000	3,000	12
1,000 < x ≤ 2,000	2,000	35
500 < x ≤ 1,000	1,000	38
x ≤ 500	500	103

The SR was calculated for a 1-mile long section with each of the 13 representative population densities shown in the second column of Table 27.

The aggregate SR graphs were created by scaling the individual 1-mile SR frequency data at each "N" value according to the number of mile segments for each population.

Using this methodology, the aggregate SR was calculated for the low speed case (speeds up to 25 mph) and high speed case (train speeds greater than 25 mph and up to 50 mph) of LNG DOT-113 transportation along the example ETS route. The aggregate SR FN curves are compared for each case in Figure 11. The aggregate societal risk profile for the example route indicates a likelihood of observing one fatality approximately once every 200 years for high speed mainline transport and approximately once every 350 years for the low speed mainline transport.

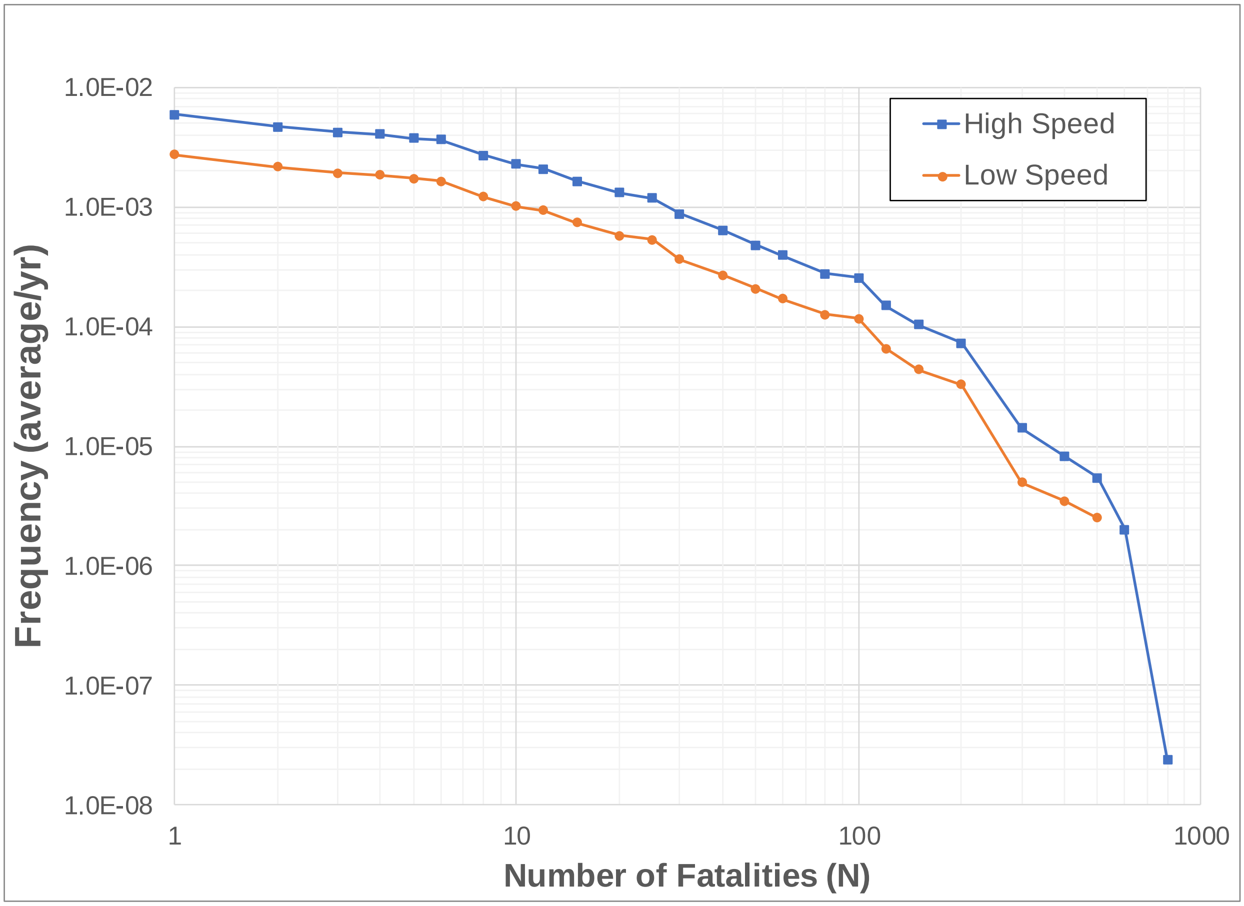

Figure 11. FN curve of the aggregate SR for the mainline train movement of LNG DOT-113s for the low speed case (up to to 25 mph) and high speed case (greater than 25 mph and up to 50 mph) along the example mainline route.

8 Limitations

As requested by Energy Transport Solutions, LLC (ETS), Exponent conducted a Quantitative Risk Assessment (QRA) study addressing unit-train movement of LNG DOT-113 tank cars by rail. The scope of services performed during this review may not adequately address the needs of other users of this report, and any use of this report or its findings, conclusions, or recommendations presented herein are at the sole risk of the user. The opinions and comments formulated during this assessment are based on observations and information available at the time of the study. The representation of NFPA 59A risk criteria in this report has been done for the purposes of comparing the transportation risk to a set of existing stationary facility quantitative risk criteria used in the U.S. and may not necessarily be appropriate or applicable for directly assessing acceptability of transportation risk. The assumptions adopted in this study do not constitute an exclusive set of reasonable assumptions, and use of a different set of assumptions or methodology might produce materially different results. Therefore, these results should not be interpreted as predictions of a loss that may occur as a result of any specific future event. Accordingly, no guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.

The findings and recommendations presented herein are made to a reasonable degree of engineering certainty. The methodology that was used in this report is based on mathematical modeling of physical systems and processes as well as data from third parties in accordance with the regulatory requirements. Uncertainties are inherent to the methodology and these may subsequently influence the results generated.

Appendix A

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Appendix B

LNG DOT-113 Unit Train Mainline Movement Event Trees

LNG DOT-113 Movement Event Trees
Mainline High Speed (25 - 50 mph)

Train Accident Rate (accidents/yr)	Derailment Probability	Probability of Number of LNG DOT-113 cars Involved in Derailment		Outcome			Calculated Outcome Frequency (/yr)
				For a Release Rate (lb/s) of …	The Probability is…		
8.83E-04	5.32E-01	1.34E-01	1 car	0	9.55E-01	=	**6.03E-05**
				3.60	1.60E-02	=	**1.01E-06**
				58.6	2.60E-02	=	**1.64E-06**
				1 CR	3.00E-03	=	**1.89E-07**
		2.17E-02	2 cars	0	9.12E-01	=	**9.31E-06**
				3.60	3.06E-02	=	**3.12E-07**
				7.20	2.56E-04	=	**2.61E-09**
				60.4	5.05E-02	=	**5.16E-07**
				117	6.76E-04	=	**6.90E-09**
				1 CR	5.98E-03	=	**6.10E-08**
				2 CR	9.00E-06	=	**9.18E-11**
		3.06E-02	3 cars	0	8.71E-01	=	**1.25E-05**
				5.40	4.45E-02	=	**6.40E-07**
				10.8	4.10E-06	=	**5.89E-11**
				62.2	7.35E-02	=	**1.06E-06**
				148	1.99E-03	=	**2.86E-08**
				1 CR	8.95E-03	=	**1.29E-07**
				2 CR	2.69E-05	=	**3.86E-10**
		1.54E-02	4 cars	0	8.32E-01	=	**6.03E-06**
				5.40	5.71E-02	=	**4.14E-07**
				12.6	1.57E-05	=	**1.14E-10**
				64.0	9.52E-02	=	**6.90E-07**
				178	3.89E-03	=	**2.82E-08**
				1 CR	1.19E-02	=	**8.63E-08**
				2 CR	5.37E-05	=	**3.89E-10**
				3 CR	1.08E-07	=	**7.83E-13**
		1.60E-02	5 cars	0	7.94E-01	=	**5.97E-06**
				5.40	6.87E-02	=	**5.17E-07**
				14.4	3.77E-05	=	**2.84E-10**
				65.8	1.15E-01	=	**8.68E-07**
				180	6.36E-03	=	**4.78E-08**
				1 CR	1.48E-02	=	**1.11E-07**
				2 CR	8.92E-05	=	**6.71E-10**
				3 CR	2.68E-07	=	**2.01E-12**
		1.40E-02	6 cars	0	7.59E-01	=	**4.99E-06**
				5.40	7.95E-02	=	**5.23E-07**
				16.2	7.23E-05	=	**4.76E-10**
				67.6	1.35E-01	=	**8.86E-07**
				155	9.33E-03	=	**6.14E-08**
				266	6.53E-06	=	**4.30E-11**
				1 CR	1.77E-02	=	**1.16E-07**
				2 CR	1.33E-04	=	**8.75E-10**
				3 CR	5.35E-07	=	**3.52E-12**
		1.49E-02	7 cars	0	7.24E-01	=	**5.05E-06**
				7.20	8.94E-02	=	**6.24E-07**
				19.8	2.02E-06	=	**1.41E-11**
				64.0	1.52E-01	=	**1.06E-06**
				76.6	1.64E-07	=	**1.15E-12**
				151	1.28E-02	=	**8.97E-08**
				262	1.48E-05	=	**1.04E-10**
				1 CR	2.06E-02	=	**1.44E-07**
				2 CR	1.86E-04	=	**1.30E-09**
				3 CR	9.34E-07	=	**6.52E-12**
		1.23E-02	8 cars	0	6.92E-01	=	**3.99E-06**
				7.20	9.83E-02	=	**5.68E-07**
				21.6	3.87E-06	=	**2.23E-11**
				71.2	1.70E-01	=	**9.79E-07**
				130	1.59E-02	=	**9.18E-08**
				218	8.78E-04	=	**5.07E-09**
				293	5.80E-07	=	**3.35E-12**
				1 CR	2.35E-02	=	**1.36E-07**
				2 CR	2.47E-04	=	**1.43E-09**
				3 CR	1.49E-06	=	**8.60E-12**
		9.43E-03	9 cars	0	6.61E-01	=	**2.93E-06**
				7.20	1.07E-01	=	**4.72E-07**
				18.0	6.67E-06	=	**2.96E-11**
				67.6	1.85E-01	=	**8.20E-07**
				160	2.10E-02	=	**9.32E-08**
				207	4.58E-05	=	**2.03E-10**
				325	5.32E-06	=	**2.36E-11**
				1 CR	2.64E-02	=	**1.17E-07**
				2 CR	3.17E-04	=	**1.40E-09**
				3 CR	2.23E-06	=	**9.88E-12**
		1.40E-02	10 cars	0	6.31E-01	=	**4.15E-06**
				7.20	1.14E-01	=	**7.52E-07**
				18.0	1.06E-05	=	**6.98E-11**
				65.8	2.00E-01	=	**1.31E-06**
				134	2.40E-02	=	**1.58E-07**
				221	1.80E-03	=	**1.18E-08**
				330	2.64E-06	=	**1.74E-11**
				1 CR	2.92E-02	=	**1.92E-07**
				2 CR	3.95E-04	=	**2.60E-09**
				3 CR	3.17E-06	=	**2.09E-11**
		7.18E-01	11 cars	0	6.03E-01	=	**2.03E-04**
				7.20	1.21E-01	=	**4.07E-05**
				18.0	1.61E-05	=	**5.42E-09**
				67.6	2.13E-01	=	**7.17E-05**
				134	2.85E-02	=	**9.61E-06**
				221	2.41E-03	=	**8.14E-07**
				330	4.72E-06	=	**1.59E-09**
				1 CR	3.20E-02	=	**1.08E-05**
				2 CR	4.82E-04	=	**1.63E-07**
				3 CR	4.35E-06	=	**1.47E-09**

* - CR = Catastrophic rupture of the DOT-113 car(s)
**- Shaded cells are descriptors and are not used in the outcome frequency values

LNG DOT-113 Movement Event Trees
Mainline Low Speed (≤ 25 mph)

			Outcome			
Train Accident Rate (accidents/yr)	**Derailment Probability**	**Probability of Number of LNG DOT-113 cars Involved in Derailment**	**For a Release Rate (lb/s) of …**	**The Probability is…**		**Calculated Outcome Frequency (/yr)**
8.83E-04	6.40E-01	2.48E-02 1 car	0	9.55E-01	=	**1.34E-05**
			3.60	1.60E-02	=	**2.24E-07**
			58.6	2.60E-02	=	**3.64E-07**
			1 CR	3.00E-03	=	**4.20E-08**
		2.34E-02 2 cars	0	9.12E-01	=	**1.21E-05**
			3.60	3.06E-02	=	**4.05E-07**
			7.20	2.56E-04	=	**3.39E-09**
			60.4	5.05E-02	=	**6.69E-07**
			117	6.76E-04	=	**8.94E-09**
			1 CR	5.98E-03	=	**7.91E-08**
			2 CR	9.00E-06	=	**1.19E-10**
		2.23E-02 3 cars	0	8.71E-01	=	**1.10E-05**
			5.40	4.45E-02	=	**5.61E-07**
			10.8	4.10E-06	=	**5.16E-11**
			62.2	7.35E-02	=	**9.26E-07**
			148	1.99E-03	=	**2.50E-08**
			1 CR	8.95E-03	=	**1.13E-07**
			2 CR	2.69E-05	=	**3.39E-10**
		1.91E-02 4 cars	0	8.32E-01	=	**8.99E-06**
			5.40	5.71E-02	=	**6.17E-07**
			12.6	1.57E-05	=	**1.69E-10**
			64.0	9.52E-02	=	**1.03E-06**
			178	3.89E-03	=	**4.20E-08**
			1 CR	1.19E-02	=	**1.29E-07**
			2 CR	5.37E-05	=	**5.80E-10**
			3 CR	1.08E-07	=	**1.17E-12**
		6.09E-01 5 cars	0	7.94E-01	=	**2.73E-04**
			5.40	6.87E-02	=	**2.36E-05**
			14.4	3.77E-05	=	**1.30E-08**
			65.8	1.15E-01	=	**3.97E-05**
			180	6.36E-03	=	**2.19E-06**
			1 CR	1.48E-02	=	**5.09E-06**
			2 CR	8.92E-05	=	**3.07E-08**
			3 CR	2.68E-07	=	**9.22E-11**

* - The probability that no LNG DOT-113 cars are involved in an accident can be determined by summing the probabilities for 1-X derailments and substracting that value from 1
** - CR = Catastrophic rupture of the DOT-113 car(s)
***- Shaded cells are descriptors and are not used in the outcome frequency values