Thermal Sciences

Florida East Coast Railway

FECR Movement of LNG ISO Containers by Rail

Quantitative Risk Analysis (QRA) Considering LNG Position in Train and Train Speed

Exponent Project No. 1308194.001

Exponent®
Failure Analysis Associates®

Florida East Coast Railway

(b) (4)

FECR Movement of LNG (b) (4) ISO Containers by Rail

Quantitative Risk Analysis (QRA) Considering LNG Position in Train and Train Speed

Exponent Project No. 1308194.001

Prepared for

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Acronyms and Abbreviations

ALARP	As Low as Reasonably Practicable
ASME	American Society of Mechanical Engineers
ATC	Automatic Train Control
BLEVE	Boiling Liquid Expanding Vapor Explosion
°C	Degrees Celsius
DNV	Det Norske Veritas
DOT	U.S. Department of Transportation
ESD	Emergency Shutdown Device
°F	Degrees Fahrenheit
FECR	Florida East Coast Railway
FN	Frequency and Severity of Outcome
FRA	Federal Railroad Administration
ft	Feet
gpm	Gallons Per Minute
gal	Gallon
GPS	Global Positioning System
GSM	Gas Supply Module
HAZID	Hazard Identification
HAZMAT	Hazardous material
HSE	UK Health & Safety Executive
IR	Individual Risk
ISO	International Standards Organization

LEL	Lower Explosive Limit
LFL	Lower Flammable Limit
LIS	Locomotive Interface System
LNG	Liquefied Natural Gas
LOC	Loss of Containment
LPG	Liquefied Petroleum Gas
MAWP	Maximum Allowable Working Pressure
MU	Multiple Unit
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
RTG	Rubber Tire Gantry
SOP	Standard Operating Procedure
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 (b) (4) Florida East Coast Railway (FECR) movement of liquefied natural gas (LNG) ISO (b) (4) tank containers by rail in freight trains. In order to assist the process safety management of the overall design, testing, and implementation project, the focus of the study was to evaluate the risk for movement of the ISO tank containers by intermodal rail transportation. This Executive Summary highlights Exponent's findings in the QRA. 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

Movements were evaluated along three proposed routes: (1) from Hialeah Yard to Port of Miami, (2) from Hialeah Yard to Port Everglades, and (3) from Hialeah Yard to Bowden Yard in Jacksonville. ISO Lift On/Lift Off activities and train movements were evaluated in four yards/intermodal facilities: (1) Hialeah Yard, (2) Bowden Yard, (3) Port Everglades, and (4) Port of Miami.

The QRA relied upon a series of concept-phase Hazard Identification (HAZID) studies performed in FECR's LNG fuel tender project[1] along with a review of intermodal Lift On/Lift Off

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[1] Exponent Project No. 1308194.000 report titled: "HAZID Study Report, Florida East Coast Railway Dual-Fuel Locomotive LNG Tender Project," issued January 2, 2015. Exponent Project No. 1308194.000 report

hazards to identify potential accident scenarios. A list of potential accident scenarios was developed from the HAZID studies, literature review, and review of FECR intermodal facilities and was used to define a reduced list of representative accidental release scenarios for the QRA.

(b) (4)

The ISO tank container movements were grouped into three distinct activities, distinguished by the type of operations and the risks present:

1. Lift On and yard movement at the Hialeah Rail Yard.
2. Mainline train movement.
3. Lift Off and yard movement at the receiving yard/intermodal facility.

The hazard scenarios corresponded to accidents involving the ISO tank, which is a (b) (4) [redacted]. 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 industryavailable databases and FRA rail accident statistics. Several conservative assumptions were applied during the analysis to estimate failure probabilities for the LNG ISOs since no specific historical data exists for this operation. 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). It was assumed that each train includes (b) LNG ISO containers single-stacked in well cars, and (b) cars were shipped every day of the year. Further, (4) each of the three routes was evaluated independently to bound the maximum potential risk by (4) assuming shipment via only one route. If the (b) LNG ISOs are split among multiple routes, then the risk calculated for each route would decrease. (4)

U.S. Census population data and Port passenger statistics were used to represent the populations surrounding the mainline rail routes, rail yards, and intermodal facilities. The populations along the proposed mainline routes were evaluated as aggregated population groupings within 1.6 miles from the rail yards and either side of the rail mainline. Along the mainline, the population was evaluated within approximately one-mile increments along the route. The maximum onemile population density was 11,800 people per square mile, which occurred in the Miami area. This population value was used to conservatively bound the risk for mainline movement of LNG ISOs.

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,

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titled: “HAZID Study Report, Florida East Coast Railway Dual-Fuel Locomotive LNG Tender Project, Updated to Reflect Chart LNG Tender,” issued October 24, 2014. Exponent Project No. 1308194.000 report titled: “Integration HAZID Study Report, Florida East Coast Railway Dual-Fuel Locomotive and LNG Tender Project,” issued December 12, 2014.

and explosions, and to calculate the resulting Individual Risk (IR) and Societal Risk (SR) for the mainline and yard/intermodal facilities. 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.

In this report, the calculated risk was benchmarked against a similar hazardous commodity—liquefied petroleum gas (i.e., propane or LPG). The quantitative risk criteria for evaluating the IR and SR used in this report were developed from 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, but these criteria are used as a reference point for evaluating the risk in this report. The risk criteria as applied in this report are summarized in the following table.

Summary of IR and SR quantitative risk criteria developed from NFPA 59A (2016) and used in this report.

IR Criteria (yr^{-1})	SR Criteria (evaluated per mile for Mainline)
Zone 1: IR $\geq 10^{-5}$	Unacceptable Above: F = 10^{-4}, N = 10 Slope = −1
Zone 2: $10^{-6} \leq$ IR $< 10^{-5}$	ALARP: Region between curves
Zone 3: $3 \times 10^{-7} \leq$ IR $< 10^{-6}$	Broadly Acceptable Below: F = 10^{-6}, N = 10 Slope = −1

E.2 Findings

The QRA generated several findings regarding shipping LNG ISOs on the FECR routes. The analysis required development of an accident model to calculate the release scenarios, which was then used to calculate the risk for various LNG ISO movement options along the routes. The risk was calculated for the rail yards and intermodal facilities by treating them as fixed facilities while the mainline risk was evaluated on a transportation route basis. Since transportation quantitative risk criteria are not typically applied in the U.S., the risk was benchmarked against a similar hazardous commodity—liquefied petroleum gas (i.e., propane or LPG) and similar risk criteria proposed for stationary LNG plants in the U.S. Finally, the Individual Risk for the intermodal facilities and mainline transportation routes was mapped to compare against potentially sensitive targets along the routes.

E.2.1 Accident Model

An accident model was developed as part of the QRA to address yard movements and mainline movements of LNG ISOs in freight trains. The intermodal facility risk also included considerations for lifting ISOs onto and off of trains. For train movements, loss of containment of LNG from an ISO 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 E-1. The sections of the report where each analysis block is described are listed in Figure E-1.

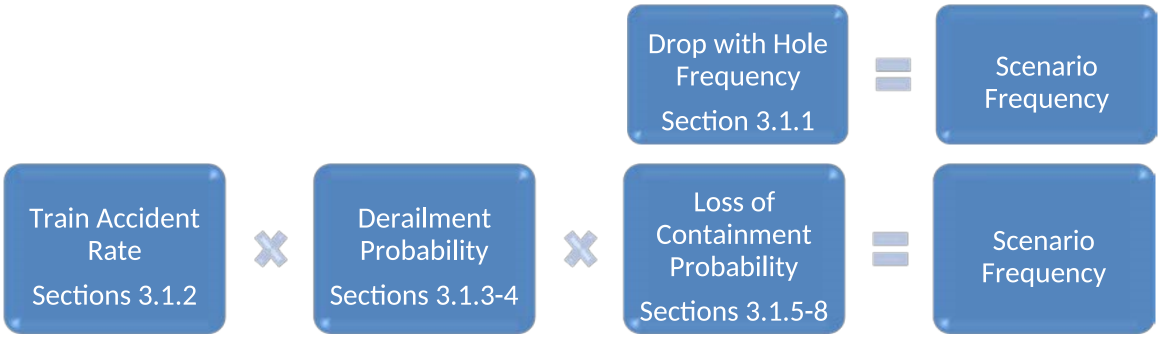

Figure E-1. LNG ISO train accident model overview.

Based on the assumed daily movement of (b)[redacted] ISO containers, the analysis accounted for (b)[redacted] lifts per day at Hialeah Yard, and another (b)[redacted] lifts per day at the receiving intermodal facility. The (4) (4) frequency for dropping an ISO that results in a 50 mm hole was found in the literature to be (4) 6.7×10^{-7} per lift. For (b)[redacted] lifts per day, this resulted in the following release frequency for each intermodal facility. (4)

LOC frequency for dropping an LNG ISO container.

Event	Release Frequency
Dropped ISO, large leak (50 mm hole)	2.2×10^{-3} yr^{-1}

FRA accident data from 1995 through 2015 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. The accident rates for the last five years is provided for comparison and are approximately 20-25% lower than the historical average. However, the QRA conservatively applied the higher accident rate in order to provide an upper bound for the risk.

Train accident rates from FRA data.

Statistic		2011-2015	1995-2015
Yard	Total Yard Train Miles	0.446×10^{9}	1.853×10^{9}
	Yard Accident Rate (/train mile)	1.55×10^{-5}	1.98×10^{-5}
Mainline	Total Non-Yard (Mainline) Train Miles	3.254×10^{9}	13.48×10^{9}
	Non-Yard Accident Rate (/train mile)	1.81×10^{-6}	2.47×10^{-6}

The position in train derailment probability was evaluated as a function of train configuration for LNG ISOs as part of the QRA. A derailment model was employed where the probability that LNG ISOs 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.

Representative probability of first car derailed for Class 1 and 2 Railroads (1995-2015).

Statistic	Car Position in Train			
	1	11	21	31
Yard Derailment Accident	24.8%	1.60%	1.20%	0.82%
Mainline Derailment Accident, Speed < 25 mph	17.3%	1.80%	1.13%	0.97%
Mainline Derailment Accident, Speed ≥ 25 to ≤ 60 mph	15.8%	1.07%	1.02%	0.80%

Average number of cars derailed (1995-2015).

Statistic	No. of Cars
Yard Derailment Accident	4
Mainline Derailment Accident, Speed < 25 mph	5
Mainline Derailment Accident, Speed ≥ 25 to ≤ 60 mph	11

Seven different train configurations were evaluated to demonstrate the effects of blocking LNG ISOs into sequential car groupings on the calculated risk. The baseline configuration (C-1) placed (b) [redacted] LNG ISOs in sequence from train position (b [redacted] to (b) [redacted] If a train accident leads to a derailment, then each configuration and speed/yard case will represent a distinct probability (4)) (4) array for multiple cars being derailed. The probability relationship for multiple cars being derailed from the baseline train configuration C-1 at high speed (≥ 25 to ≤ 60 mph) is shown in the table below. Similar relationships were developed for each train configuration, yard accidents, low speed accidents, and high speed accidents.

Probability of having X number of LNG ISO cars derail in the event of a train accident, where X is the number of LNG ISOs involved, for the baseline train configuration and mainline train movements at high speed.

Number of LNG ISOs Derailed (X)	0	1	2	3	4	5	6	7	8	9	10
Probability	59 %	17%	3.7%	3.7%	3.0%	2.1%	2.7 %	2.5%	2.3%	2.4%	2.4 %

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 sparse for (b) [redacted]
(b) [redacted] ISO containers in rail accidents, pressure tank car data was used as an analog to represent (4) (4)
pressurized ISO container 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.

LOC probability from PHMSA pressure tank car incident data and equivalent release scenario for LNG ISOs.

Quantity Released in gallons	Probability	Release Scenario
=< 100	0.958	No Release
100 < x =< 1,000	0.014	½-inch Leak
1,000 < x =< 30,000	0.025	2-inch Leak
> 30,000	0.003	Catastrophic

E.2.2 Mainline Risk

The risk posed by the LNG ISOs along the mainline was evaluated by making conservative assumptions in order to bound the maximum risk of all route options. The results are reported for the highest mainline population density value of 11,800 people per square mile. For regions of the mainline with lower population, the calculated risk will be less than that presented. Two speed ranges, low speed <25 mph and high speed ≥25 mph to ≤60 mph, were applied in the model to demonstrate the effects of train speed restrictions. Seven different train configurations were evaluated to demonstrate the effects of blocking LNG ISOs into sequential car groupings.

For example, the baseline case (C-1) placed [redacted] (b) LNG ISOs in sequence from train position [redacted] (b to [redacted] (b) This configuration poses the highest risk since all LNG ISOs are in sequence, all may be (4)) (4) involved in an individual derailment (high speed only), and the highest probability of derailment is at the front of the train. As a comparison, train configuration C-2 places the [redacted] (b) LNG ISOs in sequence from train position [redacted] (b to [redacted] (b) The table below compares the calculated risk metrics for (4) low speed and high speed movement of these train configurations along the mainline when) (4) assuming the highest population density. For slow speed train movements, the Zone 3 risk level is never reached in the analysis, and for high speed train movements, the Zone 2 risk level is never reached.

Summary of the risk metrics for mainline LNG ISO car train movements.

Risk Metric	Train Speed < 25 mph		Train Speed 25 – 60 mph	
	[redacted] (b)	[redacted] (b) (4)	[redacted] (b)	[redacted] (b) (4)

SR Integral (total risk, yr^{-1})	(4) [redacted]	(b) (4) [redacted]	(4) [redacted]	[redacted]
Maximum IR (yr^{-1})	[redacted]	(b) (4) [redacted]	[redacted]	[redacted]
Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	(b) [redacted]	[redacted]	[redacted]	[redacted]
Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	(4) (b) [redacted]	[redacted]	[redacted]	[redacted]
Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	(4) (b) [redacted]	[redacted]	[redacted]	[redacted]

(4)

E.2.3 Intermodal Facility Risk

The overall risk of LNG ISO lifting and train movement within the intermodal facilities and train yards is influenced by the contribution from lifting risk. The analysis was conducted by assuming that all lifts occurred at a single point on the intermodal ramp track, which had the effect of maximizing the Individual Risk for the facility. When the lifting is distributed along the intermodal track, the Individual Risk profile will decrease for the facility. The Individual Risk posed by train movement within the facilities yielded an Individual Risk profile that was a combination of yard track movement overlapped with lifting risk where applicable. For the facilities, the Individual Risk thresholds typically crossed the property boundaries when lifting was assumed to occur at a point, but only the Zone 3 risk threshold appeared to overlap offsite populations when lifting was modeled along the intermodal ramp track.

A summary of the risk results for the facilities is provided in the table below. For the facilities, the actual surrounding population densities were applied, and these results represent train configuration C-1. Since Individual Risk is dominated by lifting, which is independent of train configuration, other train configurations are not included. Note that the distances are from the track or point of lifting—not from the property boundary.

Summary of the risk metrics for LNG ISO train movement and ISO lifting.

Risk Metric	Hialeah	Port of Miami	Port Everglades	Bowden Yard
SR Integral (total risk, yr^{-1})	(b) (4)	[redacted]	[redacted]	[redacted]
Maximum IR (yr^{-1})	(b) (4)	[redacted]	[redacted]	[redacted]
Train Movement (from Track): Max Distance to Zone 1 - $1{\times}10^{-5}$ IR (ft)	(b)	[redacted]	[redacted]	[redacted]
Max Distance to Zone 2 - $1{\times}10^{-6}$ IR (ft)	(4) (b)	[redacted]	[redacted]	[redacted]
Max Distance to Zone 3 - $3{\times}10^{-7}$ IR (ft)	(4) (b)	[redacted]	[redacted]	[redacted]
ISO Lifting (from Point): Max Distance to Zone 1 - $1{\times}10^{-5}$ IR (ft)	(4) (b)	[redacted]	[redacted]	[redacted]
Max Distance to Zone 2 - $1{\times}10^{-6}$ IR (ft)	(4) (b)	[redacted]	[redacted]	[redacted]
Max Distance to Zone 3 - $3{\times}10^{-7}$ IR (ft)	(4) (b)	[redacted]	[redacted]	[redacted]

(4)

E.2.4 Benchmarking LNG against LPG

(b)

There is no current regulatory quantitative risk criteria for Individual Risk or Societal Risk of LNG transportation by rail, and the criteria used here were developed from those applicable to stationary LNG plants. Acceptable quantitative risk criteria for transportation of hazardous materials typically represent higher risk levels than stationary facilities. To benchmark the risk posed by LNG ISO train movements, the risk of movements of liquefied petroleum gas (propane or LPG) in the rail yards and along the mainline were analyzed. On an energy equivalence basis, (b) 10,000 gallon ISO containers of LNG were compared to 34,000 gallon DOT-112 tank (4) (4) cars of LPG.

(b)

As a result of the QRA, the transportation and handling of (b) LNG ISO containers was found to present similar or less risk than the movement of tank cars containing LPG. Accidents (4) involving LPG cars were only considered during train movements in the rail yards since no (4) lifting occurs with this car type. Overall, risk of transporting LPG was found to be comparable to LNG within the rail yards and intermodal facilities and was found to be slightly higher than LNG on the proposed routes. The overall risk for LNG ISOs in the Hialeah yard is significantly influenced by the contribution from lifting risk, which is not present for LPG. The risks between LNG and LPG are summarized in the tables below for mainline movements and for the Hialeah facility.

Comparison of risk metrics for LNG ISOs and LPG rail car mainline train movements.

Risk Metric	Train Speed < 25 mph		Train Speed from 25 – 60 mph	
	LNG	LPG	LNG	LPG

SR Integral (total risk, yr^{-1})	(b) (4)	[redacted]	[redacted]	[redacted]
Maximum IR (yr^{-1})	(b) (4)		[redacted]	[redacted]
Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	(b)	[redacted]	[redacted]	[redacted]
Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	(4) (b)	[redacted]	[redacted]	[redacted]
Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	(4) (b)	[redacted]	[redacted]	[redacted]

(4)

Comparison of risk metrics for LNG ISOs and LPG rail car movements and LNG ISO lifting in the Hialeah Yard.

Risk Metric	LNG	LPG
SR Integral (total risk, yr^{-1})	(b) (4)	[redacted]
Maximum IR (yr^{-1})	(b) (4)	[redacted]
Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	(b)	[redacted]
Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	(4) (b)	[redacted]
Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	(4) (b)	[redacted]

(4)

E.2.5 Sensitive Targets for Routes 1 and 2

The FRA requested that FECR perform an analysis of potentially sensitive establishments along the proposed railway routes. There is no current regulatory quantitative risk criteria for Individual Risk or Societal Risk of LNG transportation by rail, and the criteria used here were developed from those applicable to stationary LNG plants. For stationary LNG plants, NFPA 59A does not permit sensitive establishments, such as churches, schools, hospitals, and major public assembly areas, to be located within an Individual Risk contour greater than 3×10^{-7} per year (called Zone 3).[2] There are many differences in the hazards and risk profile between a stationary facility and a transportation activity. Acceptable quantitative risk criteria for transportation of hazardous materials typically represent higher risk levels than stationary facilities. However, the Zone 3 risk from NFPA 59A was used as the benchmark for evaluation of risk to offsite populations.

The distance to the Zone 3 contour is approximately (b) feet for high speed train movement, with high population density, and train configuration C-1 with LNG ISOs from train position (4) (b

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[2] NFPA 59A (2016) *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*, §15.10.1

(b) (4) [redacted]. By changing the train configuration, the distance to the Zone 3 contour will be decreased)(4) or eliminated entirely. For example, the C-2 configuration with (b) [redacted] LNG ISOs in sequence from train position yields a distance of (b) [redacted] feet to the Zone 3 contour. At low speed, the (4) Zone 3 contour is eliminated entirely. Only one section of the two mainline routes had listed (4) speed restriction of 25 mph or less, and this was in downtown Miami near the American Airlines Center. No Zone 3 contour was present in this area since the train was restricted to low speed. Potentially sensitive targets along Route 1 and Route 2 were identified from Google Maps, and their distance was determined from the approximate center of the track or approximate facility boundary. The following potentially sensitive targets were identified given these assumptions.

Potentially sensitive establishments along Route 1 – Hialeah to Port of Miami.

(b) [redacted]

(b) [redacted]

Establishment Name	**Category**	**Sub-Category**	**Distance to Railway**
iMater Academy Charter School	School	Public Charter School	
New Vision Emmanuel Baptist Church	Church	Self-standing church	(4)(4)
ASPIRA of Florida	School	Charter School	(b) [redacted]

(4)

*Notes: 1) Distance measurements taken from center of track to closest portion of building. 2) Identified only schools that were elementary and above

Potentially sensitive establishments along Route 2 – Hialeah to Port Everglades.

Establishment Name	**Category**	**Sub-Category**	**Distance to Railway**
iMater Academy Charter School	School	Public Charter School	(b)
New Vision Emmanuel Baptist Church	Church	Self-standing church	(4) ((4)b)
Aventura Waterways K-8 School	School	Public School	(b)
Victory Christian Center	Church	Self-standing church	(4) (b)
Hallandale Church of Christ	Church	Self-standing church	(4) (b)
Ebenezer Baptist Church	Church	Self-standing church	(4) (b)

(4)

*Notes: 1) Distance measurements taken from center of track to closest portion of building. 2) Identified only schools that were elementary and above

E.3 Limitations of the Study

As requested by Florida East Coast Railway, LLC, Exponent conducted a Quantitative Risk (b) (4) Assessment (QRA) study addressing FECR movement of LNG ISO containers 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 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

(b) (4)

Exponent conducted a Quantitative Risk Assessment (QRA) for movement of liquefied natural gas (LNG) in ISO tank containers by rail on the Florida East Coast Railway (FECR). The objective of the study was to determine the level of risk associated with the shipping of the LNG ISO containers along three potential routes in Florida. The analysis incorporated aspects of prior LNG-related rail transportation risk analyses and hazard identification studies by FECR. The QRA included typical accidental release scenarios that may lead to a loss of containment from LNG ISO containers including consideration of ISO container Lift On/Lift Off (i.e. lifting) at intermodal facilities.

The Federal Rail Administration (FRA) provided the following requirements for risk analysis of
LNG shipping by rail, which were addressed through this study:[3]

> 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, passenger rail operations on the proposed transportation lines, yards, Lift On and Lift Off areas, 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, critical infrastructures, and sensitive assets (e.g., schools, churches, playgrounds, sports arenas, elderly care/nursing homes, Emergency Medical Services, police stations, hospitals, power stations) 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.
> f. A quantitative comparison of the risks of LNG transportation in portable tanks to the risks from other flammable hazardous materials shipped on rail in portable tanks (using the volume of shipments and routes proposed for LNG shipments).

To address the FRA request, the risk of potential major incidents posed to surrounding populations was calculated during the QRA. The risk results have been presented in this

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[3] 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.

report as Individual Risk (IR) contours around the rail yard intermodal facilities and graphically as Societal Risk (SR) through an incident frequency and severity of outcome (FN) curve on a per mile basis.

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.

In this QRA report, the IR is presented in two different manners. For the intermodal facilities and rail yards at the Bowden Yard, the Hialeah Yard, Port of Miami, and Port Everglades, which are treated as fixed facilities, the IR is provided as frequency contours on aerial maps that illustrate the risk to individuals positioned within those contours. Because the LNG ISO containers will be shipped along fixed routes, release scenarios were modeled along the rail lines. There are approximately (b) [redacted] miles of rail along the line of road between Bowden and Hialeah. IR contours cannot be succinctly represented for long routes such as this, but they are (4) related to the population level along the line.[4] 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 number of potential fatalities versus likelihood from a series of potential events. The outcome of a SR analysis is a graph depicting annual frequency on the y-axis and N fatalities on the x-axis, where N is the cumulative number of potential fatalities for all scenarios represented by the corresponding cumulative frequency of events. 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

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

Transportation (DOT) Federal Railroad Administration (FRA) has not codified quantitative risk criteria for LNG hazardous materials transportation scenarios.[5] 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.[6,7,8] 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). 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)*.[9,10] 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 or portable LNG containers. Thus, the quantitative risk criteria proposed in the standard are not directly applicable to rail shipping of LNG. However, these risk criteria were used as one basis for quantitative risk criteria for rail shipping of LNG that were used in this analysis.

1.1.2 Individual Risk Criteria

NFPA 59A identifies three “Zones” representing ranges of quantitative risk criteria for evaluating IR. Each risk zone reflects general types of public occupancies recommended to be permitted. As the magnitude of the calculated risk increases, the type of occupancy becomes more restrictive. The quantitative risk criteria for IR of LNG plants are reproduced in Table 1. The occupancies not permitted in Zone 3, as described in Table 1, are referred to as “sensitive targets,” consistent with the FRA guidance document.[11] The FRA has requested

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

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

[7] 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.

[8] 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).

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

[10] 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.

[11] 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.

that FECR identify Zone 3 occupancies that are located within 500 feet of the proposed rail shipping routes. These are provided in tabular form and identified on aerial images in Appendix G.

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 the table is a result of the compilation of the outcomes calculated from an event tree of many potential fire and explosion events.

Based on Zone 3 being the most restrictive zone, any IR values less [redacted] [redacted] than (b) (4) are not of concern for the analysis in this report and 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[12] and do not account for the factors typically considered in a transportation risk analysis. However, the commonly acceptable level of IR for transportation risks on sensitive populations is 10^{-6}, which is the upper threshold for Zone 3.[13]

Table 1. Quantitative risk criteria for IR contours 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 $10^{-6} \leq IR < 10^{-5}$	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 $3 \times 10^{-7} \leq IR < 10^{-6}$	Not permitted: Churches, schools, hospitals, major public assembly areas, and other sensitive establishments Permitted: All other structures and activities

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 transportation or shipping of hazardous materials. 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

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[12] "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).

[13] 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).

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. Using a quantitative risk criterion that is based on a stationary facility will inherently limit the consideration of routes to those that are similar in dimension to a stationary facility. In fact, to address this limitation, the international regulations and guidance documents employ a scaled approach where the SR criteria are evaluated on a per unit length of route (i.e., per route kilometer) basis. Authors and regulators have concluded that in order to directly compare the analysis of transportation or pipeline risk to stationary facilities, these scenarios should consider FN curves normalized per representative unit length (which is typically on a per route kilometer basis).[14,15,16] Although many international groups and agencies also increase the stationary facility quantitative risk criteria by an order-of-magnitude when applied to transportation routes, this approach was not taken here in order to use conservative risk criteria (although increasing the thresholds by an order of magnitude may ultimately be decided as being appropriate by the stakeholders for this project). Thus, the NFPA 59A stationary facility quantitative risk criteria were used as a basis for evaluating the transportation risk results on a per track mile basis. The SR has also been calculated on a per mile basis using customary measure of distance in the U.S. for the rail routes, which is also more conservative than using a per kilometer basis (i.e., the per mile risk is approximately twice the value as a per kilometer basis). Thus, Exponent's approach was to analyze the SR for shipping LNG on a per track mile basis and use the NFPA 59A stationary facility quantitative risk criteria in order to provide conservative risk results relative to the recommended approaches relied upon by international governments and agencies.

The SR quantitative risk criteria lines, as depicted in Figure 1, will be used in this report on a per track mile basis[17] for line of road operations. The FN curves for the yards and intermodal facilities will not be normalized per mile of track length since these operations more closely resemble stationary facilities and, therefore, will include the switching areas of the yards and the intermodal loading facilities.

The SR for alternative train configurations was also evaluated by examining the SR integral,

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[14] Chapter 3.3.5 Detailed QRA, Railways, Calculation and presentation of results, p. 3.15 in *Guideline for Quantitative Risk Assessment, Part Two: Transport* (Dutch Purple Book), Publication Series on Dangerous Substances, Ministerie van Verkeer en Waterstaat (2005).

[15] Section 5.4, p. 23 in 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).

[16] Schork JM, EM Lutostansky, and SR Auvil, "Societal Risk Criteria and Pipelines," Pipeline & Gas Journal, 239(10), October 2012.

[17] Two types of mile units are used in this report: train miles and track miles. Train miles represent the distance traveled by a train, typically as an average value of miles traveled per year. Track miles represent the length or position along a fixed route along the rail line.

or the area under the FN curve. This allows for the FN curves between multiple scenarios to be easily compared to one another by representing the FN curves as a single number. To compare against the values reported for the specific scenarios, the SR integral for the upper risk criterion (labeled “unacceptable” in NFPA 59A) is 6.91×10^{-3} when integrated from 1 to 1,000 (or 4.61×10^{-3} when integrated from 1 to 100).

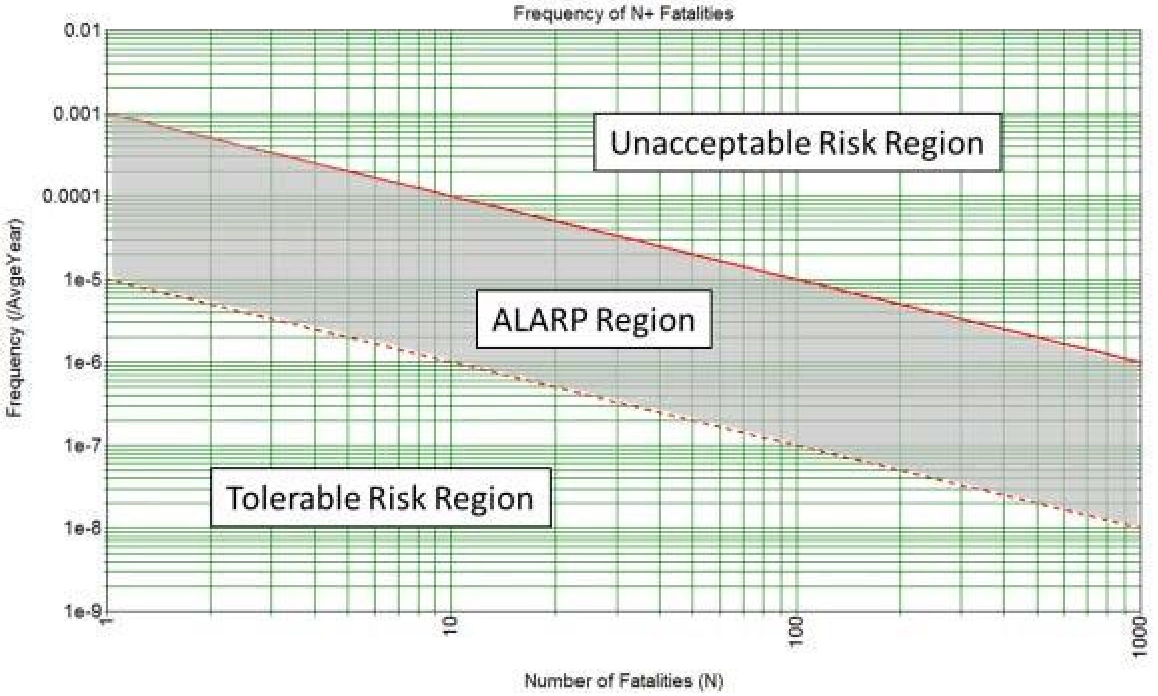


Figure 1. SR quantitative risk criteria presented on an example FN graph, as provided in NFPA 59A for fixed (stationary) LNG facilities. The definitions of the tolerable risk region, ALARP (As Low as Reasonably Practicable), and unacceptable risk region are provided by NFPA 59A, and do not necessarily reflect the tolerability criteria for transportation risk. 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 criteria used in the U.S. and may not necessarily be appropriate or applicable for assessing acceptability of transportation risk.

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 (e.g., on the order of 50 days) storage conditions, LNG ISO 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 and intermodal 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 coldtemperature 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.

1.3 Robustness of FECR Engineering and Administrative Safeguards

The Florida East Coast Railway (FECR) system includes several aspects of engineering and administrative safeguards that are consistent with FRA best practices and are anticipated to minimize the risk of train accidents such as derailments and collisions. These are discussed in detail in Appendix B. In summary, the FECR system has the following features to complement the overall safety of rail operations:

1. Automatic Train Control
2. Low elevation changes
3. Concrete ties
4. Active crossing lights and gates
5. Equipment Defect Detector system along mainline route

For example, FECR uses Automatic Train Control (ATC) on all locomotives, which is integrated into the existing full aspect cab signal system (Engineer has an illuminated color coded signal in the locomotive cab as well as a similar corresponding signal on the wayside), that mitigates the following accident risks:

1. Main-line train to train collision.
2. Engineer disregard of a red signal as a result of an unsafe track condition or switch

position.

3. Automatic application of the train brakes to a train when the engineer or conductor has not complied with a red signal indication.

The rules for ATC are provided in 49 CFR Part 236 Subpart E–Automatic Train Stop, Train Control and Cab Signal Systems.

2 Systems Description

LNG ISO tank container movements were evaluated along three proposed routes: (1) from Hialeah Yard to Port of Miami, (2) from Hialeah Yard to Port Everglades, and (3) from Hialeah

(b) (4) [redacted]

Yard to Bowden Yard (Jacksonville). The LNG will be provided by the nearby LNG facility in Hialeah, Florida. This facility has a liquefaction capacity of gallons per day; thus, the QRA assumed an average daily movement rate of (b) [redacted] 10,000 gallon ISO containers. As will be discussed below, although more containers may theoretically be shipped intermittently, the (4) overall risk is adequately represented by modeling this annual average movement capacity.

(b) (4) [redacted]

The ISO tank container movements were grouped into three distinct activities, distinguished by the type of operations and the unique risks present:

1. Lift On at Intermodal Facility in Hialeah Rail Yard
2. Mainline train movement
3. Lift Off at Intermodal Facility

The following sections will provide more details on the ISO tank containers, intermodal operations, and the proposed train routes.

(b) (4) [redacted]

2.1 ISO Tank Containers

(b) (4) [redacted]

The LNG will be transported in ISO cryogenic portable tank containers (ISOs). The ISOs are certified against the International Maritime Organization – International Maritime Dangerous Goods Code, Volume 1, which is incorporated into the specific federal code – Title 49 Code of Federal Regulations (CFR) Part 172.519(f). The ISOs are designed to be transported as intermodal freight by railroad, tractor-trailer, and marine vessel, in order to reduce the need for transfer between containers during transport from the liquefaction facility and the end customer. (b) (4) [redacted]

The (b) [redacted] ISO is comprised of an (b) (4) [redacted]

(b) [redacted]

The ISO containers are designed for LNG service. Some design parameters are listed in Table 2, and Figure 2 is a copy of the general assembly drawing. The ISOs will operate at psig and will be fitted with pressure relief safety valves set at the Maximum Allowable Working

Pressure (4)

(MAWP) [redacted] of (b) psig. The saturation temperature (i.e., boiling point) for [redacted] LNG at the operating pressure of (b(4)) (4)

Table 2. (b) ISO tank container design parameters. (4)

Parameter	Value
Operating Pressure (psig)	(b)
Design Pressure (psig)	(4) (b)
MAWP (psig)	(4) (b)
Design Temperature (°C)	(4) (b)
Operating Temperature (°C)	(4) (b)
Net Volume (gal)	(4) (b) (4)

(b) (4)

Figure 2. General assembly drawing for LNG (b) ISO portable tank containers to

be used by FECR. (4)

Figure 3 is a copy of the piping and instrumentation diagram (P&ID) for the (b) [redacted] ISO tank container, which depicts the piping connections to the inner tank. The piping connections to the inner tank are the following:

- (b) (4) [redacted]

Images of a representative ISO container are provided in Figure 4, Figure 5, and Figure 6. Figure 4 is a photograph of one of the LNG (b) [redacted] ISO portable tank containers mounted on an intermodal truck chassis at the offsite LNG loading station. Figure 5 is a picture of the rear of the chassis depicting the closed valve cabinet. Figure 6 is a photograph of the valves and outer tank penetrations inside the valve cabinet. The pressure relief valve array is located above the cabinet inside the frame. (b) (4) [redacted]

(b) (4) [redacted]

Figure 3. Piping and instrumentation diagram for (b) [redacted] ISO portable tank container.

D15997 - 0051

(b) (4)

Figure 4. ISO tank container mounted on a truck chassis.

D15997 - 0045

(b) (4)

Figure 5. Rear view of ISO portable tank container on a truck chassis depicting the valve cabinet.

Figure 6. View of valves and outer tank penetrations inside valve cabinet.

2.2 Intermodal Facility Operations

The filled LNG ISOs will be transferred onto well cars at the Hialeah Yard intermodal facility. The operation of transferring the LNG ISOs from the truck chassis to the well cars is termed "Lift On," and transferring from well cars back to truck chassis is termed "Lift Off." After movement on a train along a given route, the ISOs will be lifted off the well cars and attached to truck chassis at the receiving intermodal yard. This risk analysis does not address over the road transport or storage of LNG ISOs; only the train movement and Lift On/Lift Off activities are considered. Additionally, empty ISOs pose minimal hazardous material risks; thus, the return of empty ISOs was not analyzed.

FECR contracts (b) (4) to operate and maintain lifting equipment for transferring ISO containers from truck chassis onto well cars. Truck chassis are driven within the intermodal yard by local drivers who may be either FECR contractors or Port contractors. The truck chassis are positioned near the trains on the intermodal facility ramp area. Figure 7 and Figure 8 show the two types of container lifting equipment used in the intermodal facilities. Trained (b) (4) (b) (4) cranes (b) (4) or (b) (b) operators control depending upon the logistics for each train. The ISOs will be lifted onto or off of single well cars in the FECR intermodal facilities. ISOs will not be double-stacked in the well cars; only one ISO will be stacked in each well car. A representative image of a well car loaded with two 20-ft ISO portable tank containers at an FECR intermodal facility is provided in Figure 9. The

LNG ISO container would occupy the equivalent space to these two smaller ISOs. (4) (4)

D15997 - 0088

(b) (4) [redacted]

Figure 7. crane used for Lift On/Lift Off of intermodal containers.

D15997 - 0101

(b) (4)

Figure 8. used for Lift On/Lift Off of intermodal containers.


D15997 - 0132

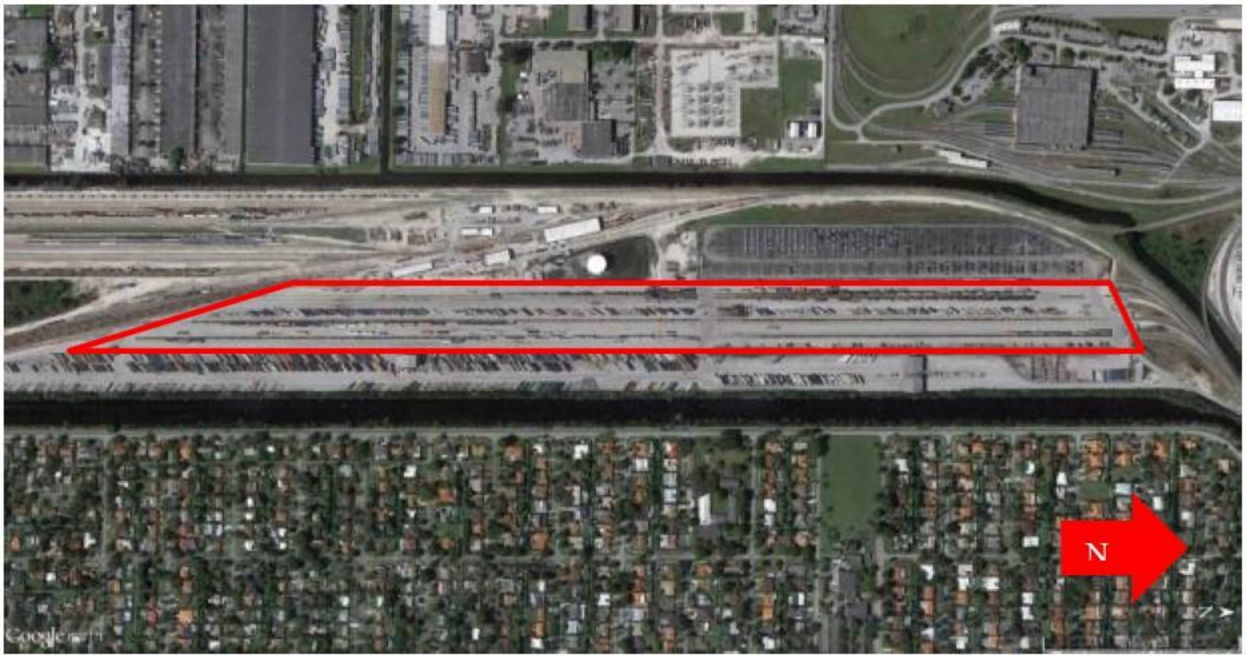
Figure 9. Representative well car in FECR intermodal yard containing two 20-ft ISO portable tank containers. One LNG ISO would replace these two containers in the proposed service.

2.2.1 Aerial Views of Intermodal Facilities

The equipment, procedures, and operating practices were reported to be equivalent for all four intermodal facilities. Aerial images of the rail yards and intermodal facilities are provided in the following figures.

Google Earth image, circa January 2016

Figure 10. Aerial image of the FECR **Hialeah Rail Yard** (enclosed in red outline). Trains enter and leave the Hialeah Yard at the right side of the image. North is to the right in the image. The rail yard is surrounded on three sides by a canal. Industrial occupancies are located to the north, west and south. Residential areas are located to the east.



Google Earth image, circa January 2016

Figure 11. Close-up view of the FECR **Hialeah Intermodal Facility** intermodal ramps (area outlined in red) where containers are lifted on and off of rail cars.

Google Earth image, circa January 2016

Figure 12. Dodge Island, which contains the **Port of Miami** (enclosed in red outline). The Port includes container ship docks (yellow hashed lines) and cruise ship docks (white hashed lines).

Google Earth image, circa January 2016

Figure 13. FECR **Port of Miami Intermodal Facility** (enclosed in red outline) intermodal ramps.

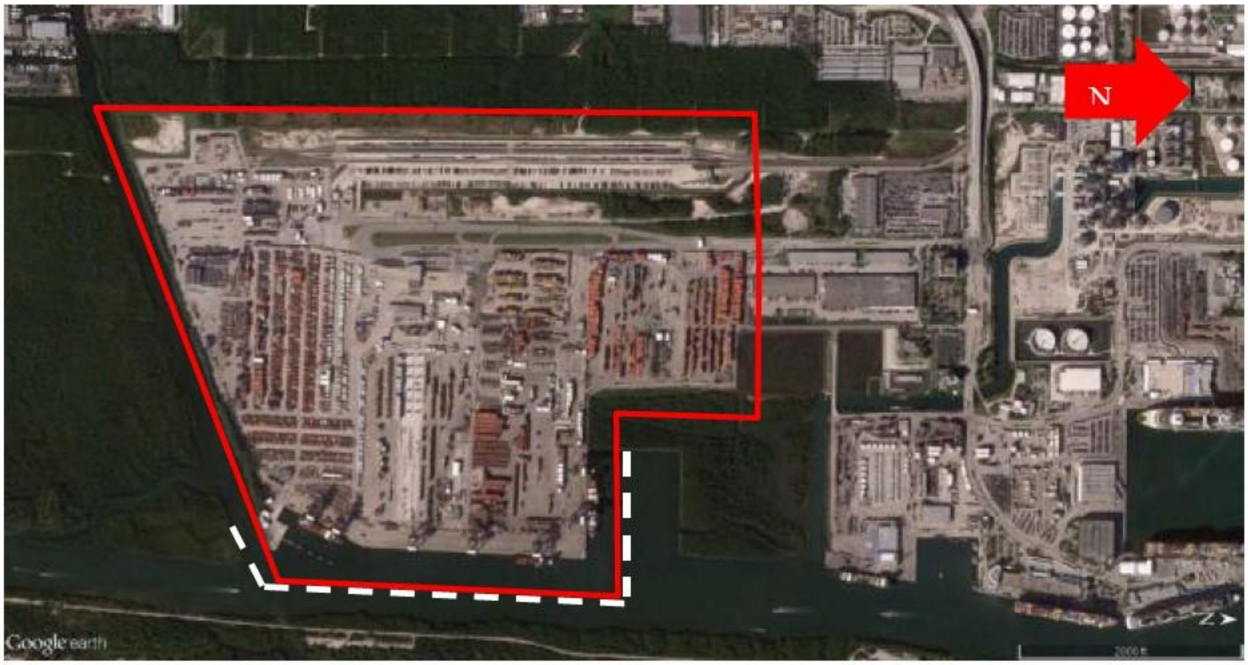


Figure 14. Aerial image of the **Port Everglades Intermodal Area** (enclosed in red outline). North is to the right in the image. The FECR intermodal facility is located to the west (top) of the intermodal container storage area. The Port includes container ship docks (white hashed lines) and cruise ship docks located farther to the north (right side of image).

Figure 15. FECR **Port Everglades Intermodal Facility** (enclosed in red outline) intermodal ramps and container staging area.

Figure 16. Aerial image of the **FECR Bowden Rail Yard** (enclosed in red outline). North is to the lower right in the image. The FECR intermodal facility is located to the north (right) of the yard.

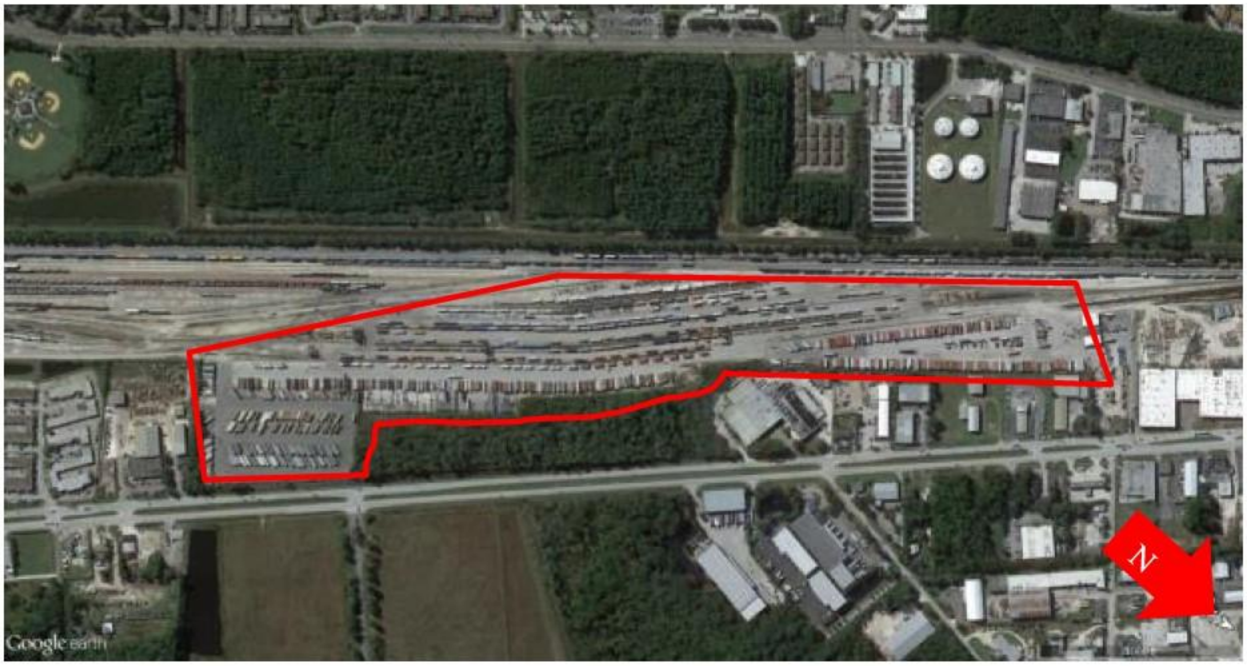


Figure 17. FECR **Bowden Intermodal Facility** (enclosed in red outline) intermodal ramps and container staging area.

2.3 LNG ISO Movement Routes

Movements were evaluated along three proposed routes: (1) From Hialeah Yard to Port of Miami, (2) From Hialeah Yard to Port Everglades, and (3) Hialeah Yard to Bowden Yard (Jacksonville). Train movements were evaluated within the respective train yards and along the mainline track to these destinations. The maps for the routes and the mainline in the following figures were provided by FECR (additional information is provided in Appendix C). These maps were used as the basis for the train routes in the QRA. The total estimated track mileage and train mileage for each route are supplied in Table 3.

As a conservative assumption, each route was analyzed independently by assuming that each (b) (4) [redacted] route handled . This conservative approach may overestimate the risk for each route depending upon the actual annual average of ISOs shipped per route since an average of (b [redacted]) ISOs per day may be split between the three routes.

Table 3. Routes and estimated mileage.

Route	Route Length (track miles)	Total Estimated Annual Route Length (train miles)
Route 1	15	(b) [redacted]
Route 2	28	(4) (b) (4) [redacted]
Route 3	364	(b) (4) [redacted]

Figure 18. Route 1 - Hialeah Yard to Port of Miami. FECR route is traced in blue. North is up.

Figure 19. Route 2 - Hialeah Yard to Port Everglades. FECR route is traced in blue. North is up.

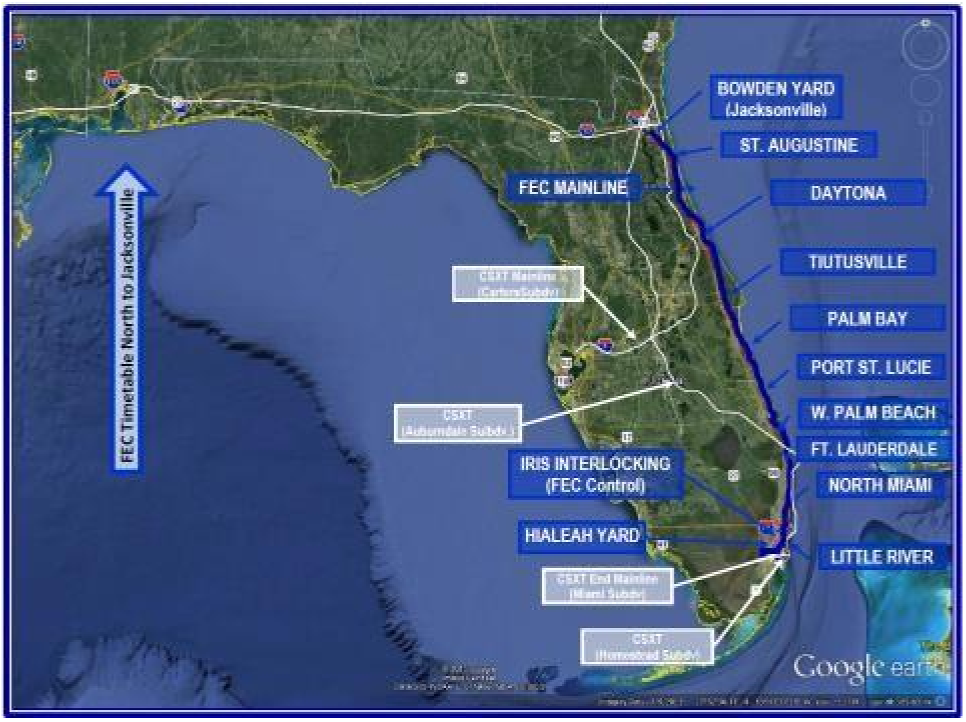


Figure 20. Route 3 - Hialeah Yard to Bowden Yard along the FECR mainline. FECR route is traced in blue. North is up.

3 Methodology

The QRA was conducted by applying PHAST Risk software to evaluate a series of accident scenarios involving the transportation of LNG along the three proposed routes and at the intermodal facilities. The objective of the analysis was to quantify the Individual Risk (IR) and Societal Risk (SR) for populations surrounding the Hialeah Yard, Port Everglades, Port of Miami, the Bowden Yard, and the rail lines along the three routes.

The design of the UN (b) [redacted] ISO portable tank is final, and several ISOs have been made available for use in LNG service along FECR's routes. Engineering and administrative systems (4) that may be employed to reduce the likelihood or the severity of releases in the intermodal facilities and along the routes 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 LNG ISO containers along three proposed routes and movements within the intermodal facilities.

In consultation with FECR, a list of representative transportation scenarios was developed for analysis in the QRA. Three unique LNG handling and ISO movement scenarios are considered:

1. Lift On of LNG ISO containers onto rail cars at Hialeah Rail Yard Intermodal Facility.
2. LNG movement on rail, either in the yard or on the mainline.
3. Lift Off of LNG ISO containers from rail cars at the destination intermodal facility.

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 LNG ISO 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[18] 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.

(b) (4)

Figure 21 provides a flow chart identifying each step of the risk assessment process. A further discussion of these key QRA parameters, as considered and evaluated for the proposed FECR shipping of ISO containers project, is provided in subsequent sections.

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[18] 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.

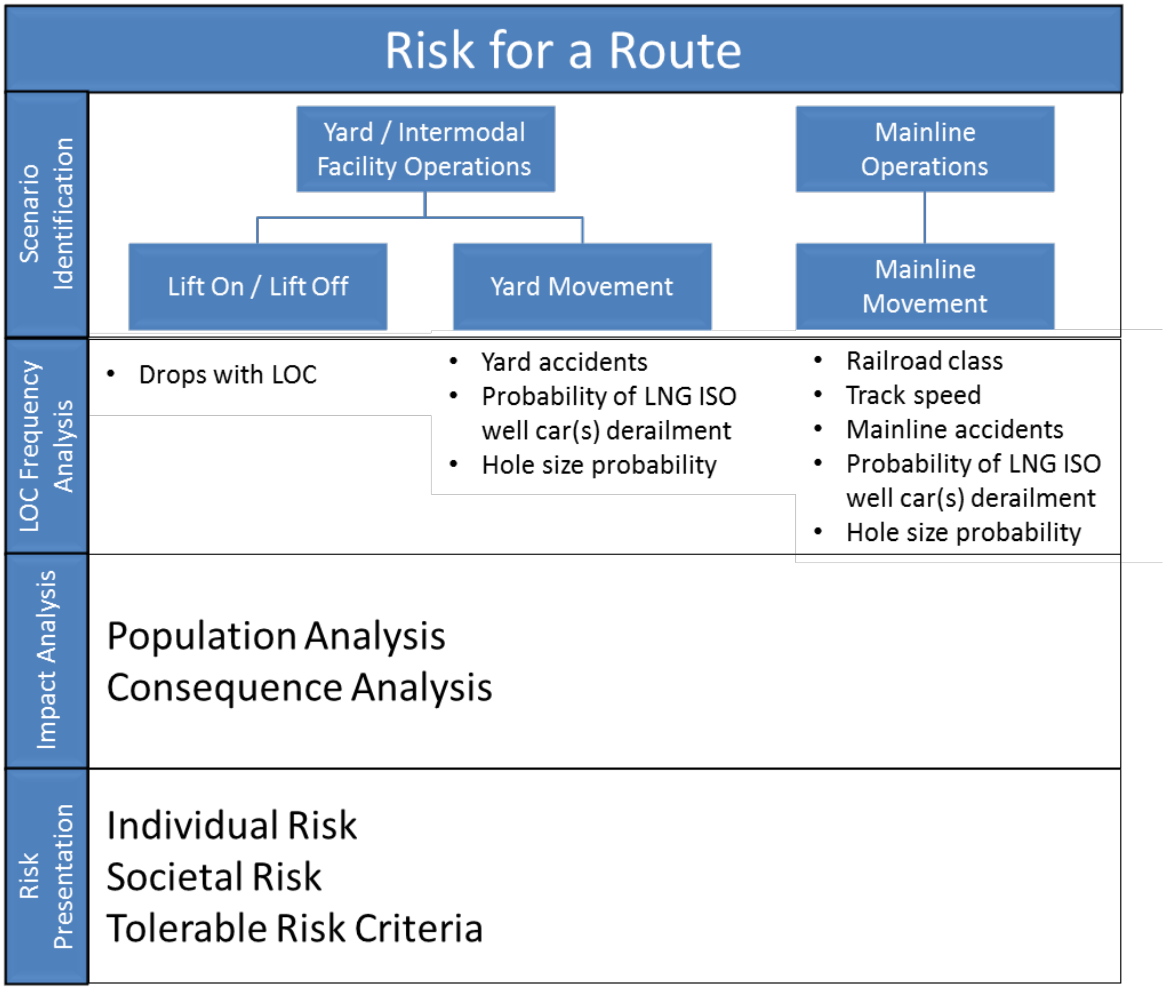

Figure 21. General approach for risk analysis in the QRA.

Given the nature of the project, several variables were approximated or estimated to provide this QRA. For example, accident rates involving (b) ISO containers in intermodal shipping via rail in the US are not available. Currently, the Federal Railroad Administration (FRA) has not (4) codified guidelines for acceptable risk to individuals or society. Thus, the risk values are compared to quantitative risk criteria for stationary LNG facilities provided by NFPA 59A as recommended by the FRA team. The representation of NFPA 59A risk criteria for IR and SR 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. Additionally, the risk profiles for LNG shipping are compared to another hazardous material (HAZMAT) as requested by the FRA; FECR, along with many other railroads, currently ships propane by rail so this was used as a benchmark comparison for the risk of shipping LNG in ISO containers.

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 one or more ISOs. The rate of mainline train accidents was applied to shipping along the routes. The rate of yard train accidents and dropping of ISO containers during lifts was applied to the rail yards and intermodal facilities. No QRA-ready databases of train accidents and LOC probabilities existed for LNG ISOs. 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 22, 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.

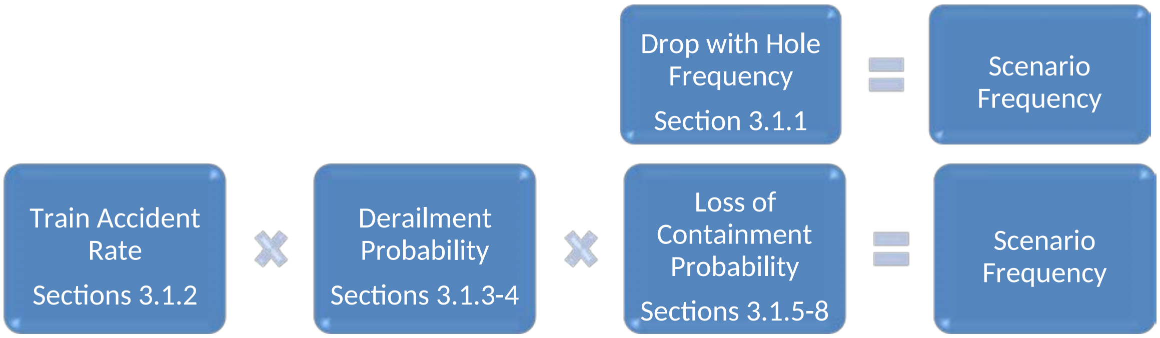

Figure 22. LNG ISO train accident model overview.

3.1.1 Lifting Accident Rates and LOC Probabilities

Lifting of the ISO containers onto rail cars occurs at the Hialeah Yard Intermodal Facility; they are then lifted off at the destination intermodal facility. Given the safety management systems (e.g., training, independent verification of twist-lock engagement, equipment maintenance, etc.) at FECR's intermodal facilities, the predominant hazard considered during this operation was a dropped ISO container during Lift On/Lift Off operations. No FECR or general U.S. drop rates were available for intermodal operations at rail yards, but international failure rates were available. It is reasonable to assume that an international failure rate would apply to this operation since intermodal freight is shipped internationally. The UK Health and Safety Executive (HSE)[19] estimates a rate of 6×10^{-7} drops per lift will result in a 50 mm (2-inch) diameter hole for ISO tank containers (Table 4), for lifts at a height of less than 5 meters (16.4 feet). These conditions apply to Lift On/Lift Off of ISOs into well cars since they will be singlestacked.

Table 4. Lifting operation LOC rate due to drops.

Description	Frequency (lift^{-1})
50 mm (2-inch) hole	6.7×10^{-7}

3.1.2 Train Accident Rates

LNG shipping by rail is historically uncommon in recent U.S. rail industry history; thus, accident data that are directly comparable to movement of LNG ISO containers do not exist. Thus, Exponent analyzed publicly-available data from the FRA to estimate train accident rates for the QRA. Potential train accidents may occur in a yard when trains are assembled, during

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[19] *Failure Rate and Event Data for use within Risk Assessments*, UK Health and Safety Executive (June 28, 2012).

switching activities, and when trains travel in the yard and along the line of road. Due to the frequency of simultaneous operations and other factors, accident rates are typically higher in a rail switching yard than on the line of road. However, the speed of trains in yards is significantly slower on average than on mainline track. Thus, at lower speeds, the accident outcomes (e.g., derailment or LOC) are also anticipated to be less likely in rail yards than on mainline track. The following discussion will provide an overview of application of the available data to estimating potential LNG ISO 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.[20] Accidents in the database include broken equipment, highway grade crossing collisions, train collisions, and derailments. FECR operates a relatively small line with fewer trains, fewer train miles traveled, and fewer potential hazardous materials incidents than Class 1 railroads and many other short-line railroads. In order to provide a larger basis of operation for conservatively estimating accident rates on FECR's line, the industry data was used and applied to FECR's train miles.

The FRA industry-wide database for train accidents with reportable damage data[21] was first queried and downloaded for all accident reports during the twenty-one year period from 19952015, yielding a total count of 70,072 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 an ISO. There were, on average, 3,337 total accidents reported per year for the overall rail industry. The FRA data was filtered for all accidents from 1995-2015 (all railroad classes), and the results were analyzed to determine accident frequency for one of two cases: (1) yard accidents and (2) mainline accidents. The values are summarized in Table 5 for accidents and derailments from this data.

Table 5. Analysis of train accidents from FRA data.

	Statistic	2011-2015	1995-2015
Yard Accidents	Total Accidents	6,907	36,742
	Total Derailments	4,812	26,204
	% of All Accidents	54.0%	52.4%
	Probability that Derailment Occurs	69.7%	71.3%
Mainline, Speed < 25mph	Total Accidents	4,007	22,817
	Total Derailments	2,527	15,709
	% of All Accidents	31.3%	32.6%
	Probability that Derailment Occurs	63.1%	68.8%

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

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

Mainline, Speed = 25mph	Total Accidents	128	899
	Total Derailments	79	652
	% of All Accidents	1.0%	1.3%
	Probability that Derailment Occurs	61.7%	72.5%
Mainline, Speed from ≥ 25 to ≤ 60 mph	Total Accidents	1,640	9,189
	Total Derailments	712	5,149
	% of All Accidents	12.8%	13.1%
	Probability that Derailment Occurs	43.4%	56.0%

The raw accident numbers were then divided by train mileage to develop accident frequency estimates for the QRA. Operational data tables provided by the FRA were used to determine the total number of yard and mainline[22] train miles for the period from 1995-2015 for all classes of railroad represented in the data.[23] The operational data tables did not subdivide the mainline train miles according to track speed; thus, a single train accident frequency value was applied to all mainline train movements regardless of train speed. Using the total accident and total mileage values, the accident frequency (on a per train mile basis) were then calculated. The average accident frequencies were found to be 1.98×10^{-5} and 2.47×10^{-6} (accidents/train mile) for the yard travel and mainline travel, respectively. These were compared against the accident frequencies for the 5-year period from 2011-2015 which were found to be 1.55×10^{-5} and 1.81×10^{-6} (accidents/train mile) for the yard travel and mainline travel, respectively. Although the 5-year data demonstrates a reduction in accident rate versus the 21-year data, the 21-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 3.1.3). The results are summarized in Table 6.

Table 6. Train accident rates from FRA data.

	Statistic	2011-2015	1995-2015
Yard	Total Yard Train Miles	0.446×10^{9}	1.85×10^{9}
	Yard Accident Rate (/train mile)	1.55×10^{-5}	1.98×10^{-5}
Mainline	Total Non-Yard (Mainline) Train Miles	3.25×10^{9}	13.5×10^{9}
	Non-Yard Accident Rate (/train mile)	1.81×10^{-6}	2.47×10^{-6}

The mainline accident frequencies[24] from Table 6 were then multiplied by the total number of annual train miles estimated for each route (Table 3) to arrive at the yearly accident frequency (accidents per year). A summary of the calculated annual accident rates for each route is provided in Table 7. Again, this analysis conservatively assumes that the planned travel of ten LNG ISO's per day arrive at a single destination (in reality, the destination may change from day-to-day or the ISOs may be split and sent along more than one of the routes).

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

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

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

Thus, the accident rate for each route is anticipated to be smaller than that assumed here leading to a conservatively high accident rate for each route. The yard accident rates were applied to the intermodal facilities assuming travel across the facility once per day.

Table 7. Calculated annual accident frequencies for the mainline portion of the 3 FECR routes.

Route	Estimated Total Annual Route Length (train miles/yr)	Accident Frequency (accident/train mile)	Calculated Annual Accident Frequency (accident/yr)
Route 1	5,475	2.47×10^{-6}	1.35×10^{-2}
Route 2	10,220	2.47×10^{-6}	2.52×10^{-2}
Route 3	132,860	2.47×10^{-6}	3.28×10^{-1}

The train accident values shown above estimate the frequency that a train accident will occur somewhere along FECR's rail line. However, a train accident doesn't necessarily lead to a condition where an LOC of an LNG ISO may occur. Therefore, it was assumed that only train accidents leading to the derailment of cars could potentially result in an LOC (as discussed in more detail in Section 3.1.3). The 21-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 three cases: (1) yard movement, (2) mainline movement with train speeds from 25 mph and 60 mph, and (3) mainline movement with train speeds less than 25 mph.[25] As listed in Table 5, the calculated results indicate that in 71.3% of yard train accidents, the accident will lead to derailment of at least one rail car. The other accident-leading-to-derailment probabilities were found to be 68.8% for mainline movement with train speeds less than 25 mph and 56.0% for mainline movement with train speeds between 25 mph and 60 mph. These are the probabilities of at least one car being derailed in a train accident; however, there is a different probability that the derailment will involve LNG ISOs. The calculation of the probability that an accidentleading-to-derailment involves LNG ISOs is addressed in the next section.

3.1.3 Derailment Probability for LNG ISO-Containing Well Cars

Not all accidents-leading-to-derailment will involve an LNG ISO car, as most of the cars in an FECR train are expected to contain freight other than an LNG ISO. Several factors are expected to affect the likelihood than an LNG ISO car is derailed including: (1) the position of the LNG ISO car(s) within the train and (2) the number of LNG ISOs grouped together. These two factors were explored in estimating the derailment probability for LNG ISO cars. First, 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. This model was then applied to trains containing LNG ISOs in a parametric study to evaluate various train configurations.

3.1.3.1 Probability of Derailment and Number of Cars Derailed

The probability of derailment for one or more LNG ISO 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 ISOs in the train. These parameters are expected to be affected by both the type of train movement (yard versus mainline) and the train speed, which were explored here using the FRA 21-year accident data.

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[25] Note that 25 mph data was included in the high speed mainline accident rates, however the 25 mph data is shown separately in Table 5 to illustrate that including the 25 mph data in the low speed (i.e. < 25 mph) derailment probabilities would be expected to result in a negligible change to the resulting risk profiles.

The FRA 21-year accident data from 1995-2015 was first filtered to include only those accidents for Class 1 and Class 2 railroads. The resulting Class 1 and 2 railroad accidents were then subdivided into either yard accidents or mainline accidents. The mainline accidents were then further split into either low speed mainline accidents with train speeds less than 25 mph or high speed mainline accidents with train speeds inclusive between 25 mph and 60 mph. Next, the accidents for the three cases were filtered in the database by including only accidents resulting in derailment. The average number of cars derailed for each of the three cases was then calculated (rounded up to whole numbers):

Case 1. Yard derailments, average number of cars derailed = 4

Case 2. Mainline derailments, speed < 25 mph, average number of cars derailed = 5

Case 3. Mainline derailments, speed 25-60 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 derailed plus the immediately following sequence of *n*-1 cars would derail, where *n* is the average number of cars derailed. The derailment statistics indicate that although the accident frequency is higher in yards relative to mainline movements, there are fewer cars derailed on average in yard derailments compared to mainline derailments. 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 was then placed into a histogram based on the position of the first car derailed. An example plot for the mainline derailments with train speeds between 25 mph and 60 mph is provided in Figure 23. The first car derailed plots for mainline derailments for train speeds less than 25 mph (Figure 24) and yard derailments (Figure 25) are similar.

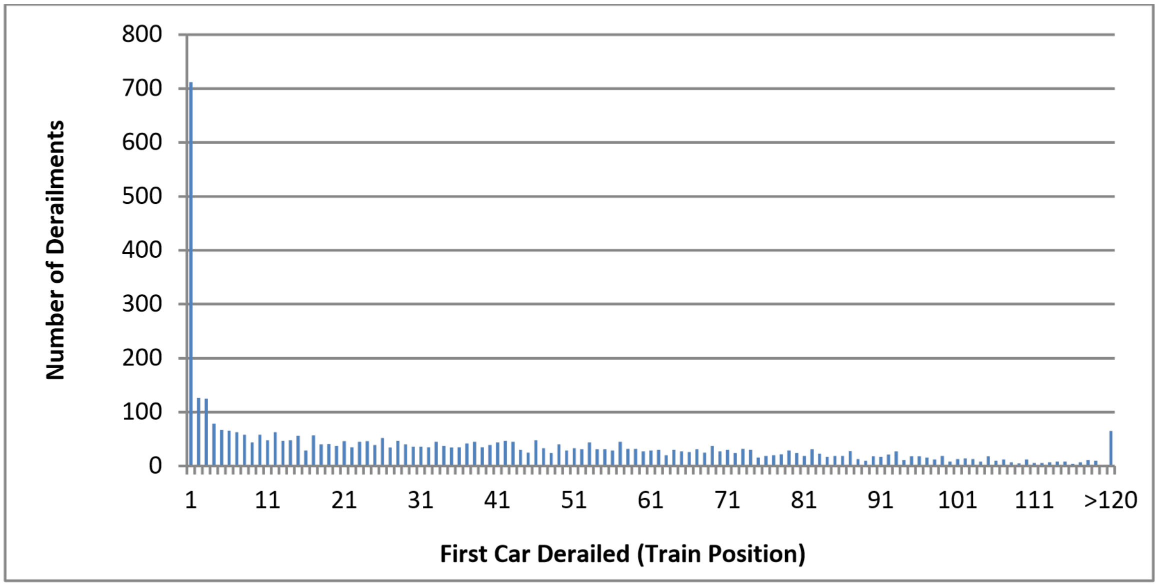

Figure 23. Frequency (count) of the first car position-in-train for mainline derailments with train speeds between 25 mph and 60 mph (total count equals 5,149

derailments).[26]

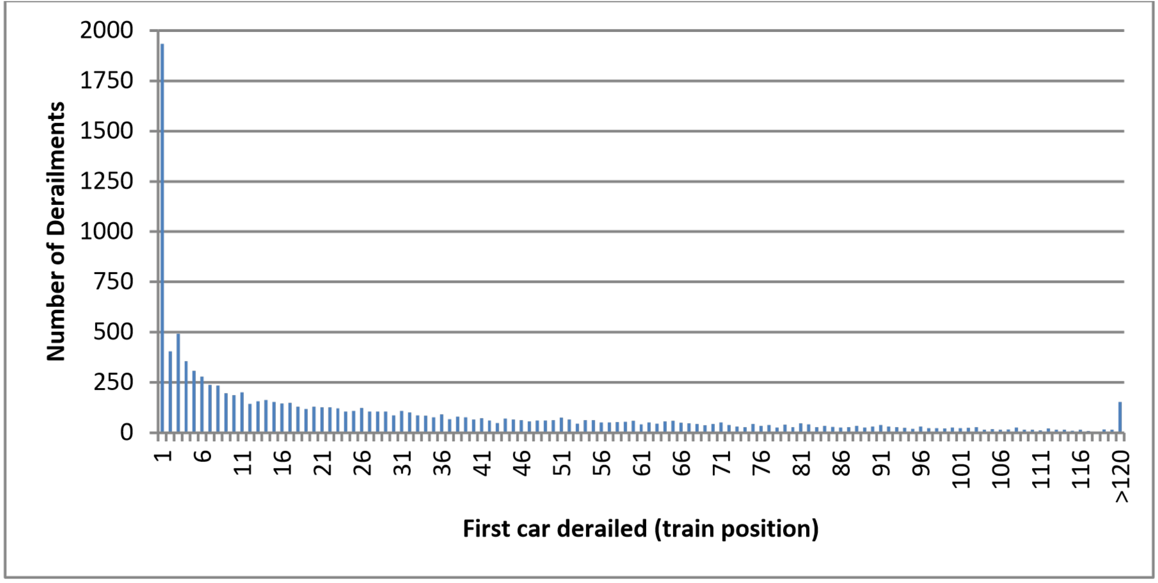

Figure 24. Frequency (count) of the first car position-in-train for mainline derailments with train speeds less than 25 mph (total count equals 15,709 derailments).

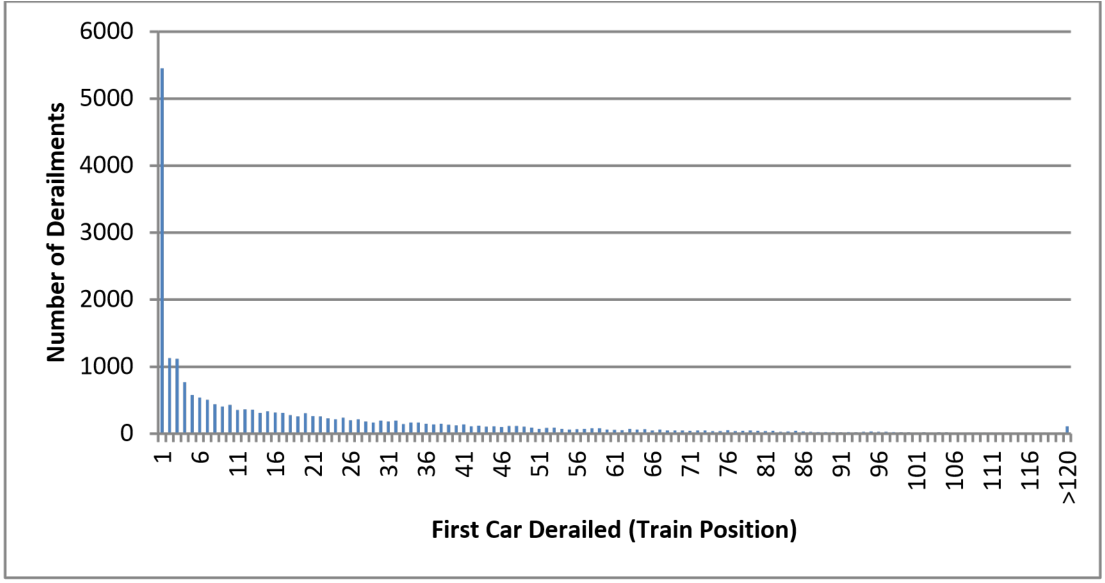

Figure 25. Frequency (count) of the first car position-in-train for yard derailments (total count equals 26,204 derailments).

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 23, the first car derailed is one of the first ten cars in nearly a third (31%) of all mainline derailments where train speeds are between 25 mph and 60 mph. Similar results are found for the percentage of derailments starting with a car in position 1-10 for the other two cases: 52% for yard

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[26] Note that the value of approximately 80 at the 120 car position in the histogram represents the sum of all cars from 120 up to 200 listed in the database.

derailments and 41% for mainline derailments where train speeds are less than 25 mph. Representative probability of first car derailed versus position are provided in Table 8. The probability of the first car derailed and the average number of cars derailed were then used to undertake a parametric sensitivity analysis for the probability of LNG ISO car derailment for various LNG ISO train configurations.

Table 8. Representative probability of first car derailed for Class 1 and 2 Railroads (1995-2015).

Statistic	Car Position in Train			
	1	11	21	31
Yard Derailment Accident	24.8%	1.60%	1.20%	0.82%
Mainline Derailment Accident, Speed < 25 mph	17.3%	1.80%	1.13%	0.97%
Mainline Derailment Accident, Speed ≥ 25 to ≤ 60 mph	15.8%	1.07%	1.02%	0.80%

3.1.3.2 Parametric Analysis of Train Configurations

Using the assumption that a train would contain [redacted] (b) LNG ISO's, multiple train configurations were explored for the purpose of calculating the probability that multiple LNG ISO cars are (4) derailed in a train accident. For example, [redacted] (b) sequential LNG ISO cars will have a different probability distribution for number of cars derailed and release quantities than other LNG ISO (4) car groupings (e.g., groups of [redacted] (b) groups of [redacted] (b) (4) etc.). However, there are some constraints on placement of LNG ISOs in a train. For example, there must be at least (4) [redacted] (b) buffer cars between the first HAZMAT car and the front of the train. Also, trains will have a finite length (4) depending upon the route and schedule. Thus, our analysis conservatively started with the first LNG ISOs no closer than car position [redacted] (b and no further back in a train than car [redacted] (b) The resulting sensitivity analysis of multiple train configurations was used to identify optimum LNG) (4) ISO placement in a train. The following train configurations in Table 9 were considered in order to represent the effects of LNG ISO position and grouping within trains, and the configurations are illustrated schematically in Figure 26.

Table 9. Train configurations evaluated in the analysis.

Train Configuration ID	Description
C-1	·· [redacted] ()Train positions: [redacted] b LNG ISO cars in sequence [redacted] (b) (4)
C-2	·· [redacted] ()Train positions: [redacted] b LNG ISO cars in sequence [redacted] (b) (4)
C-3	• Two groups of LNG ISO cars [redacted] ([redacted] (b) (4) · Separated by 5 buffer cars b · Train positions:
	• Two groups of [redacted] (LNG ISO cars

(b) (4)

C-4 · Separated by 10 buffer cars b · Train positions:

(b)

• groups of LNG ISO cars and ((

C-5 · (4)single car Separated by 10 buffer cars b b

(b) (4)

• Train positions:

• (b) groups of LNG ISO cars (

C-6 ·· (4)Separated by 10 buffer cars Train positions: b

(b) (4)

(b) (4)

(b)

• (b) groups of LNG ISO cars

C-7 · (4)Separated by 5 buffer cars (4)

(b) (4)

Train positions: (b) (4)

(b) (4)

Figure 26. Schematic representation of the blocking of LNG ISOs into consist configurations C-1 to C-7.

The probability of first car derailed as a function of position-in-train was calculated for the three cases (yard, low speed, and high speed). This data was then analyzed using the average number of cars derailed for each case to calculate the probability of having from one to ten LNG ISOs derail for the seven configurations described above.[27] A summary of the calculated probabilities is provided in Table 10 for mainline derailments with speeds between 25 mph and 60 mph.

(b) (4) [redacted]

[redacted]	[redacted]						
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

The data for Case 3 demonstrate a significant reduction in the probability of having any LNG ISOs involved in a derailment ("Total" row from table) when moving from train configuration 1 (C-1) to train configuration 2 (C-2). However, the total probability of any number of cars derailing is not the only parameter to consider when minimizing the risk. The total probability increases from C-2 to C-3, but the number of LNG ISOs involved decreases from (b) (4) [redacted] Thus, the total magnitude of the potential outcomes of C-3 will be less than C-2. As the configurations move from C-3 to C-7, the total probability increases but the maximum number of LNG ISOs involved in the derailment decreases. Using this approach allowed the

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[27] Only Configurations 1-4 were considered for the yard derailment and mainline derailments with speeds less than 25 mph cases.

permutations of LNG ISO car groupings in the train to be optimized for the QRA to reduce the risk.

The probabilities for the other two cases are provided in Table 11 for mainline derailments with speeds less than 25 mph and Table 12 for yard derailments. Only Configurations 1-4 were evaluated for these two cases. Although the total probability of having an LNG ISO involved in a derailment decreases from C-1 to C-2 for both cases, the maximum number of cars involved doesn’t change for any of the configurations considered for either case. This is because the average number of cars derailed is only five cars for mainline derailments with speeds less than 25 mph and only four cars for yard derailments, compared to eleven cars for mainline derailments with speeds between 25 mph and 60 mph.

Table 11. Case 2 - Mainline train accident with derailment for train speeds less than 25 mph. Probability of having X number of LNG ISOs derailing in the event of a train accident with derailment, where X is the number of LNG ISOs involved. On average, 5 cars are involved in a derailment for this scenario.

(b) (4)

Table 12. Case 1 - Yard train accident with derailment. Probability of having X number of LNG ISOs derailing in the event of a train accident with derailment, where X is the number of LNG ISOs involved. On average, 4 cars are involved in a derailment for this scenario.

(b) (4)

Although the derailment data for train speeds exactly 25 mph was included in the high speed (i.e. 25 – 60 mph) case, Table 13 depicts what the derailment probabilities would look like had the 25 mph data been included in the low speed (i.e. < 25 mph) case. By comparison to Table 11, it is expected that including the 25 mph data in the low speed risk analysis would have a negligible effect on the resulting risk profiles.

Table 13. Mainline train accident with derailment for train speeds less than and equal to 25 mph. On average, 5 cars are involved in a derailment for this scenario. These derailment probabilities were not used in the analysis but are shown here to illustrate the minimal effect of including the 25 mph data in the low

(b) (4) [redacted]

3.1.4 Derailment of LPG Rail Cars

LPG (UN1075) was identified as a reasonable comparison HAZMAT commodity to compare against LNG. The risks associated with the shipping of LNG ISO cars were compared to the transportation risks associated with LPG cars. The LPG rail cars were assumed to be DOT-112 pressurized rail cars (nominal volume of 34,000 gallons). The LPG transportation analysis did not include Lift On/Lift On risks since they were inapplicable, but yard movement and mainline movement were applicable. When LNG ISOs were compared to LPG rail cars on an energy-equivalent basis, it was found that approximately (b)(4) [redacted] 34,000 gallon LPG rail cars have the same energy content as (b)(4) [redacted] 10,000 gallon LNG ISOs.[28] Thus, (b)(4) [redacted] LPG cars were used in the derailment probability calculations.

The same base train accident and derailment statistics described in Section 3.1.2 were applied to the LPG cars since the type of rail car was independent of the accident and derailment statistics. The derailment probability for LPG car involvement was calculated similar to the LNG ISO cars

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[28] (b) (4) [redacted]

using only one baseline train configuration: all three LPG cars are assumed to be in series starting at train position 11. This configuration is consistent with the LNG train configuration 1 (C-1). As with the LNG ISO cars, three cases (yard, low speed, and high speed) were considered for determining the probability of LPG car involvement in the event of a train accident with derailment.

The probability of first car derailed as a function of position-in-train was then calculated for the three cases using the 21-year FRA data. This data was then analyzed using the average number of cars derailed for each case to calculate the probability of having from one to three LPG rail cars derail. A summary of the calculated probabilities is provided in Table 14.

Table 14. Probability of having X number of LPG rail cars derailing in the event of a train accident with derailment, where X is the number of LPG rail cars involved.

# of LPG Rail Cars Derailed	Probability of X Number of LPG Rail Cars Derailing		
	Mainline ≥ 25 & ≤ 60 mph	Mainline < 25 mph	Yard
(b)(4)	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]

3.1.5 ISO LOC Probabilities

The prior sections detailed the development of accident rate and derailment probability estimates for LNG ISO 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.

(b)

LOC probability data for LNG ISO containers 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 LNG ISOs. A flow chart supplementing the following discussion is provided in Figure 27 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.[27] 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 ISO containers. The analysis assumed that LOC could only occur if the LNG ISO well car was derailed. The PHMSA

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

database did not readily provide accident data for ISO portable tank containers, but it did list pressure tank car

LOC accidents. Although there are differences between the (4) (b) [redacted] ISO construction and a DOT112 pressure tank car, the dynamics and consequences of LOC are reasonably similar. Thus, (4) 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 2014, 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 5,152 pressure tank car incidents[28] 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).[29,30] These volumes were chosen as the PHMSA data appeared to reflect mostly 30,000+ gallon tank cars in contrast to the 10,000 gallon ISO container used for LNG transportation.

Representative hole sizes were chosen for each release category, in line with a previous quantitative risk assessment completed for FECR.[32] Small releases were modeled using a ½inch hole while a 2-inch hole was used for large releases. These hole sizes are consistent with appurtenance sizes on the ISO container. 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 15.

Table 15. PHMSA pressure tank car incident data from 1971-2014 and equivalent release scenarios based on a sensitivity analysis of spill diameters.

Quantity Released in gallons	Incident Count	Probability	Release Scenario
=< 100	4,937	0.958	No Release
100 < x =< 1,000	73	0.014	½-inch Leak
1,000 < x =< 30,000	127	0.025	2-inch Leak
> 30,000	15	0.003	Catastrophic

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[28] As of November 14, 2014.

[29] 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).

[30] Exponent report titled: "Florida East Coast Railway Dual-Fuel Locomotive and LNG Tender Project Quantitative Risk Assessment Report," issued January 2, 2015.

The LOC probabilities estimated here are based on data for all pressurized tank car accidents, and it was not possible to differentiate between yard and mainline accidents. It is anticipated that yard accidents will result in a decreased probability of LOC relative to mainline accidents due to lower travel speeds (and, therefore, less kinetic energy and smaller net forces generated during accidents). Based on the rail tank car QRA analysis guidelines published in the Dutch Purple Book, it is expected that the probability of outflow for low speed (i.e., yard) accidents is a factor of 10 less than that for high speed (i.e., mainline) accidents.[31] However, it was conservatively assumed that the LOC probabilities for yard accidents involving ISOs are the same as those on the mainline in the QRA.

As a comparison, Jeong et al. developed a probabilistic puncture model for head impact to general tank cars as a function of wall thickness.[32] The authors analyzed proprietary accident data collected since 1960 by the Railway Supply Institute and the Association of American Railroads (AAR). They found that their 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 15 above.

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[31] Table 3.7, Probability of outflow (> 100 kg) given an accident, 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).

[32] 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).

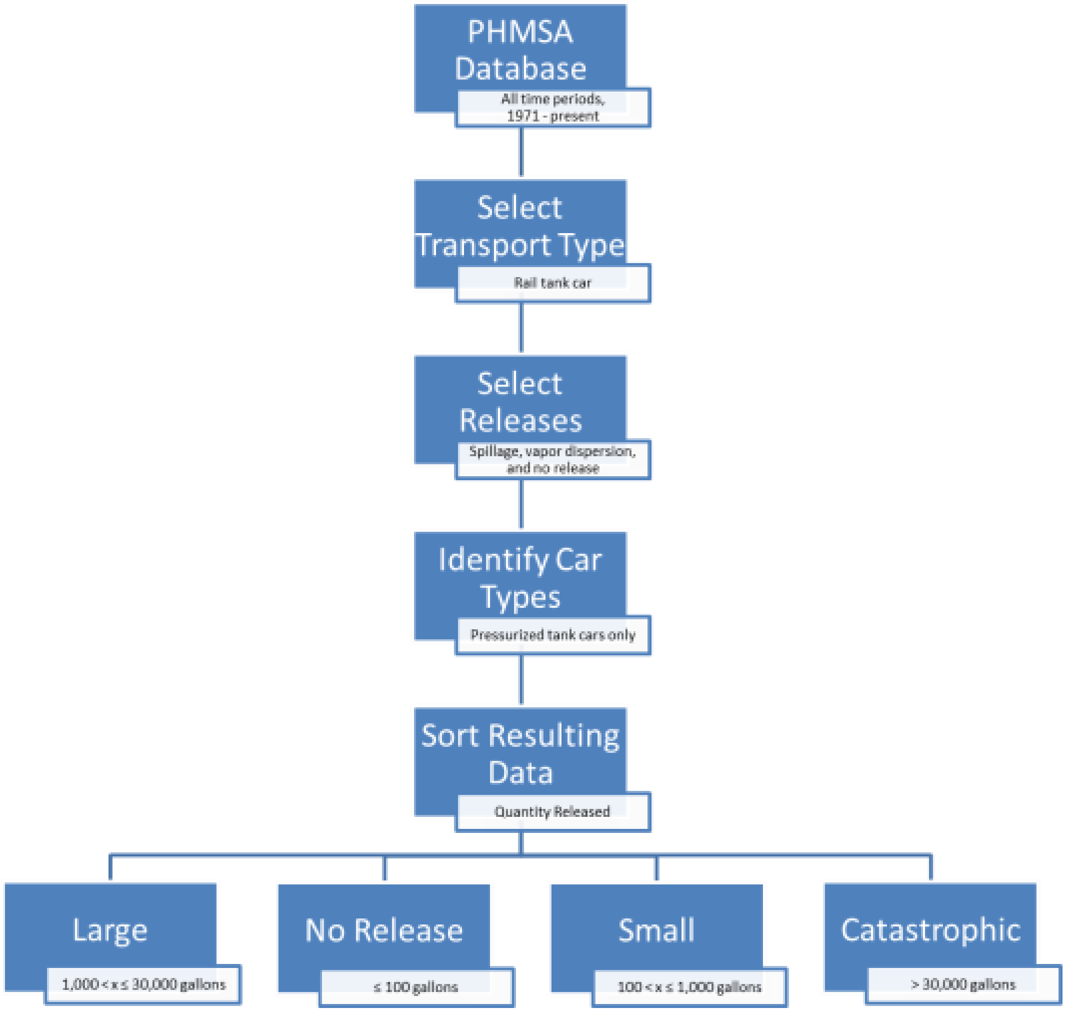

Figure 27. Flow chart describing the LNG ISO LOC probability estimation approach.

3.1.6 LPG Rail Car LOC Frequency

The risks associated with the transportation of LNG ISO cars was compared to the transportation risks associated with LPG cars. The LPG rail cars were assumed to be transported in DOT-112 pressurized rail cars (nominal volume of 34,000 gallons). The LNG ISOs were compared to LPG rail cars on an energy-equivalent basis; it was estimated that approximately

(b) (4)

The PHMSA database included data for propane DOT-112 cars involved in accidents. Estimated outflow frequency and corresponding effective hole sizes were developed by analyzing this data from 1971 to 2014.[33] The data set was filtered to include only UN1075 commodity accidents for the LPG tank car outflow frequencies. The data were then sorted and filtered by quantity released in order to estimate outflow frequencies. A histogram approach was taken, and spill volumes were ordered into logical groupings consistent with

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

the intent of the QRA and the approach for LNG. Any spill less than 100 gallons was assumed as no release, spills between 100 and 1,000 gallons were a small spill (0.5-inch hole), spills between 1,000 and 30,000 gallons were a large spill (2-inch hole), and spills greater than 30,000 gallons were considered as a catastrophic release. A summary of the rail transport outflow frequency estimates versus spill size used in this study are provided in Table 16. The LOC probabilities for each spill volume range were remarkably similar to the statistics for all pressure cars.

Table 16. Rail transport outflow frequencies for LPG rail car accidents.

Quantity Released in gallons	Incident Count	Probability	Release Scenario
=< 100	2,293	0.945	No Release
100 < x =< 1,000	32	0.013	½-inch Leak
1,000 < x =< 30,000	84	0.035	2-inch Leak
> 30,000	17	0.007	Catastrophic

3.1.7 Multiple LNG ISO 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 ISO for all leak scenarios. Consolidated release rates ranged from 0 to approximately 100 kg/s depending upon the case. None of the permutations led to a catastrophic release of more than three LNG ISOs. The consolidated releases for accidents involving two through ten LNG ISOs are shown in Table 17 through Table 25.

Table 17. Consolidated release scenarios for two LNG ISOs.

Equivalent release rate (kg/s)	Probability
0	9.18×10^{-1}
1.57	2.70×10^{-2}
19.4	4.86×10^{-2}
37.6	6.25×10^{-4}
Catastrophic Rupture (1 ISO)	5.98×10^{-3}
Catastrophic Rupture (2 ISOs)	9.00×10^{-6}

Table 18. Consolidated release scenarios for three LNG ISOs.

Equivalent release rate (kg/s)	Probability
0	8.79×10^{-1}
2.01	3.91×10^{-2}
20.0	7.09×10^{-2}
40.8	1.84×10^{-3}
Catastrophic Rupture (1 ISO)	8.95×10^{-3}

Catastrophic Rupture (2 ISOs)	2.69×10^{-5}

Table 19. Consolidated release scenarios for four LNG ISOs.

Equivalent release rate (kg/s)	Probability
0	8.42×10^{-1}
2.51	5.03×10^{-2}
20.6	9.18×10^{-2}
38.8	3.54×10^{-3}
59.0	6.11×10^{-5}
Catastrophic Rupture (1 ISO)	1.19×10^{-2}
Catastrophic Rupture (2 ISOs)	5.37×10^{-5}
Catastrophic Rupture (3 ISOs)	1.08×10^{-7}

Table 20. Consolidated release scenarios for five LNG ISOs.

Equivalent release rate (kg/s)	Probability
0	8.07×10^{-1}
3.03	6.07×10^{-2}
21.1	1.12×10^{-1}
39.4	5.74×10^{-3}
57.6	1.48×10^{-4}
77.4	1.91×10^{-6}
Catastrophic Rupture (1 ISO)	1.48×10^{-2}
Catastrophic Rupture (2 ISOs)	8.92×10^{-5}
Catastrophic Rupture (3 ISOs)	2.68×10^{-7}

Table 21. Consolidated release scenarios for six LNG ISOs.

Equivalent release rate (kg/s)	Probability
0	7.73×10^{-1}
3.58	7.03×10^{-2}
21.7	1.30×10^{-1}
39.9	8.37×10^{-3}
58.1	2.87×10^{-4}
76.4	5.54×10^{-6}
Catastrophic Rupture (1 ISO)	1.77×10^{-2}
Catastrophic Rupture (2 ISOs)	1.33×10^{-4}
Catastrophic Rupture (3 ISOs)	5.35×10^{-7}

Table 22. Consolidated release scenarios for seven LNG ISOs.

Equivalent release rate (kg/s)	Probability
0	7.41×10^{-1}
4.14	7.92×10^{-2}
22.3	1.48×10^{-1}
40.5	1.14×10^{-2}
58.7	4.88×10^{-4}
76.9	1.26×10^{-5}
95.1	1.94×10^{-7}
Catastrophic Rupture (1 ISO)	2.06×10^{-2}
Catastrophic Rupture (2 ISOs)	1.86×10^{-4}
Catastrophic Rupture (3 ISOs)	9.34×10^{-7}

Table 23. Consolidated release scenarios for eight LNG ISOs.

Equivalent release rate (kg/s)	Probability
0	7.09×10^{-1}

4.77	1.06×10^{-1}
22.9	1.64×10^{-1}
41.1	1.48×10^{-2}
59.3	7.59×10^{-4}
77.5	2.44×10^{-5}
95.7	5.02×10^{-7}
Catastrophic Rupture (1 ISO)	2.35×10^{-2}
Catastrophic Rupture (2 ISOs)	2.47×10^{-4}
Catastrophic Rupture (3 ISOs)	1.49×10^{-6}

Table 24. Consolidated release scenarios for nine LNG ISOs.

Equivalent release rate (kg/s)	Probability
0	6.80×10^{-1}
5.30	9.48×10^{-2}
23.5	1.79×10^{-1}
41.7	1.84×10^{-2}
59.9	1.11×10^{-3}
78.1	4.27×10^{-5}
96.3	1.10×10^{-6}
Catastrophic Rupture (1 ISO)	2.64×10^{-2}
Catastrophic Rupture (2 ISOs)	3.17×10^{-4}
Catastrophic Rupture (3 ISOs)	2.23×10^{-6}

Table 25. Consolidated release scenarios for ten LNG ISOs.

Equivalent release rate (kg/s)	Probability
0	6.51×10^{-1}
5.88	1.02×10^{-1}
24.1	1.94×10^{-1}
42.3	2.24×10^{-2}
60.5	1.54×10^{-3}
78.7	6.92×10^{-5}
96.9	2.14×10^{-6}
Catastrophic Rupture (1 ISO)	2.92×10^{-2}
Catastrophic Rupture (2 ISOs)	3.95×10^{-4}
Catastrophic Rupture (3 ISOs)	3.17×10^{-6}

3.1.8 Multiple LPG Rail Car LOC Frequency

The same strategy utilized for consolidating the LNG ISO car LOC frequencies was used for the LPG cars. As with the LNG ISO cars, the outcomes were also refined by eliminating all potential LOC events with probabilities less than 1×10^{-7} as this is expected to result in an outcome with negligible risk (regardless of outcome). The consolidated release scenarios for involvement of two and three LPG rail cars are provided in Table 26 and Table 27.

Table 26. Consolidated release scenarios for two LPG rail cars.

Equivalent release rate (kg/s)	Probability
0	8.93×10^{-1}
2.87	2.47×10^{-2}
35.5	6.71×10^{-2}
68.9	1.23×10^{-3}
Catastrophic Rupture (1 LPG car)	1.39×10^{-2}
Catastrophic Rupture (2 LPG cars)	4.90×10^{-5}

Table 27. Consolidated release scenarios for three LPG rail cars.

Equivalent release rate (kg/s)	Probability
0	8.44×10^{-1}
3.69	3.53×10^{-2}
36.6	9.64×10^{-2}
69.9	3.52×10^{-3}
103.3	4.29×10^{-5}
Catastrophic Rupture (1 LPG car)	2.07×10^{-2}
Catastrophic Rupture (2 LPG cars)	1.46×10^{-4}
Catastrophic Rupture (3 LPG cars)	3.43×10^{-7}

3.2 Flammable Cloud Formation

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 28):

- 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 timevarying 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.[34] The PHAST-UDM has also been approved by PHMSA for analyzing LNG vapor dispersion exclusion zones.[35]

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.

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[34] 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.

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

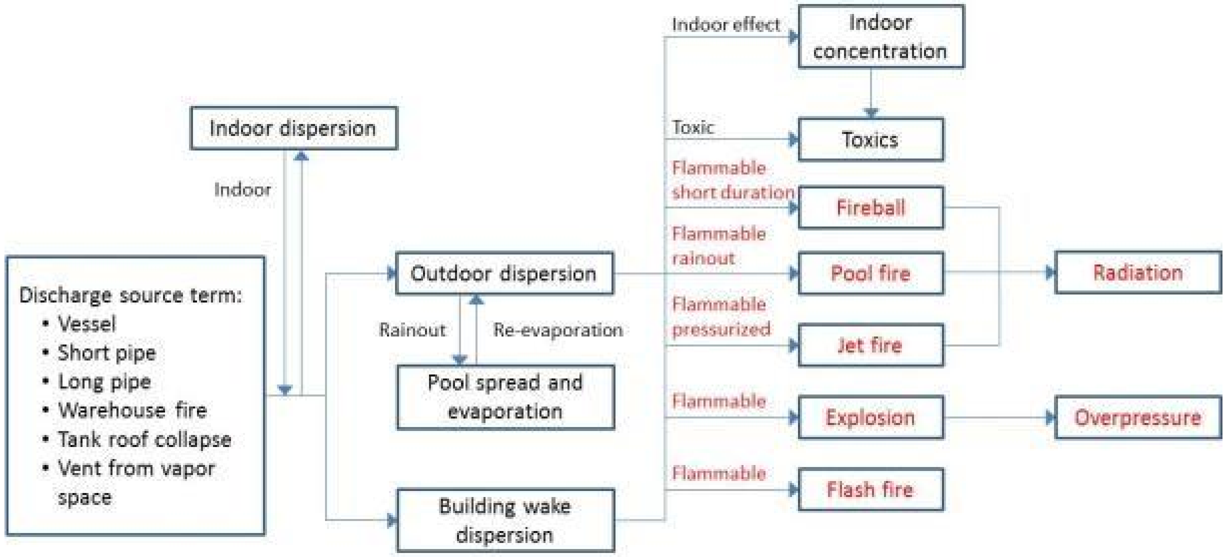

Figure 28. Block diagram for PHAST.

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. The immediate and delayed ignition probabilities in PHAST Risk are consistent with the guidelines published in the Dutch Purple Book.[36,37] 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.

3.3.1 Probability of Immediate Ignition

The “stationary” immediate ignition probability is dependent on the specific release characteristics for the scenario including the leak rate for a continuous release, the storage volume for an instantaneous/catastrophic release, and the material released. Methane is defined as a low reactivity material in the software, and the probability of immediate ignition has 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 ISOs 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.

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

[37] 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 28 lists the probability of immediate ignition for the scenarios identified in the QRA.

Table 28. Probability of immediate ignition for methane in PHAST Risk

Hole Size	Stationary	Rail Tank Car
0.5-inch	0.02	0.1
2-inch	0.04	0.1
Instantaneous	0.09	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 "stationary" and "tank wagon." 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. 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.

The delayed ignition probability for a given grid cell is then calculated from the equation,

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

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 flammable cloud is present in the grid cell located at (x,y), $\omega_{x,y}$ is the ignition effectiveness factor for that 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 on the population specified in the domain. The probability of delayed ignition increases with increasing population which then increases the overall risk as population increases.

3.4 Flammable Effects on a Population

The flammable effects resulting from a release of LNG include pool fires, jet fires, flash fires, and BLEVEs. 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[38] (and applied to QRA in the Dutch Purple Book[39]).[40] 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 BLEVE, 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.

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):

- BLEVE, 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 pressures exceeding 1.45 psig (0.1 barg) are considered have a probability of fatality 2.5% of the time. All other exposures are not considered fatalities. The Baker-Strehlow-Tang (BST) explosion method is used to calculate the overpressure profile for explosion. The BST model inputs are provided in Table 29. The clouds were conservatively assumed to entirely occupy congested regions.

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[38] 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).

[39] 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).

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

Table 29. Model inputs for the Baker-Strehlow-Tang (BST) modeling of explosions in PHAST Risk.

Parameter	Value
Material Reactivity	Low
Flame Expansion Factor	3
Obstacle Density	Low
Ground Reflection Factor	2
Congested Fraction	100%

3.4.1 Flammable Effects Event Trees

The flammable effects resulting from a release of LNG include pool fires, jet fires, flash fires, and BLEVE. 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 fraction of LNG that flashes immediately upon release with the remainder raining out on the ground, forming a pool, subsequently vaporizing, and/or leaving a persistent pool. The event tree used in PHAST to represent the probabilistic outcomes for these continuous releases with rainout is provided in Figure 29.

Similar event trees exist for a continuous release with no rainout and an instantaneous release with rainout, all scenarios examined in this study. The structure of the event trees is consistent with guidance in the Dutch Purple Book.[41] 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.[42] For the example event tree provided in Figure 29, the delayed ignition branch has a 60% probability of resulting in a flash fire and a 40% probability of resulting in an explosion (there is zero probability for no effect); the residual pool fire has a probability of 15% and "no effect" is 85% for that branch.

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

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

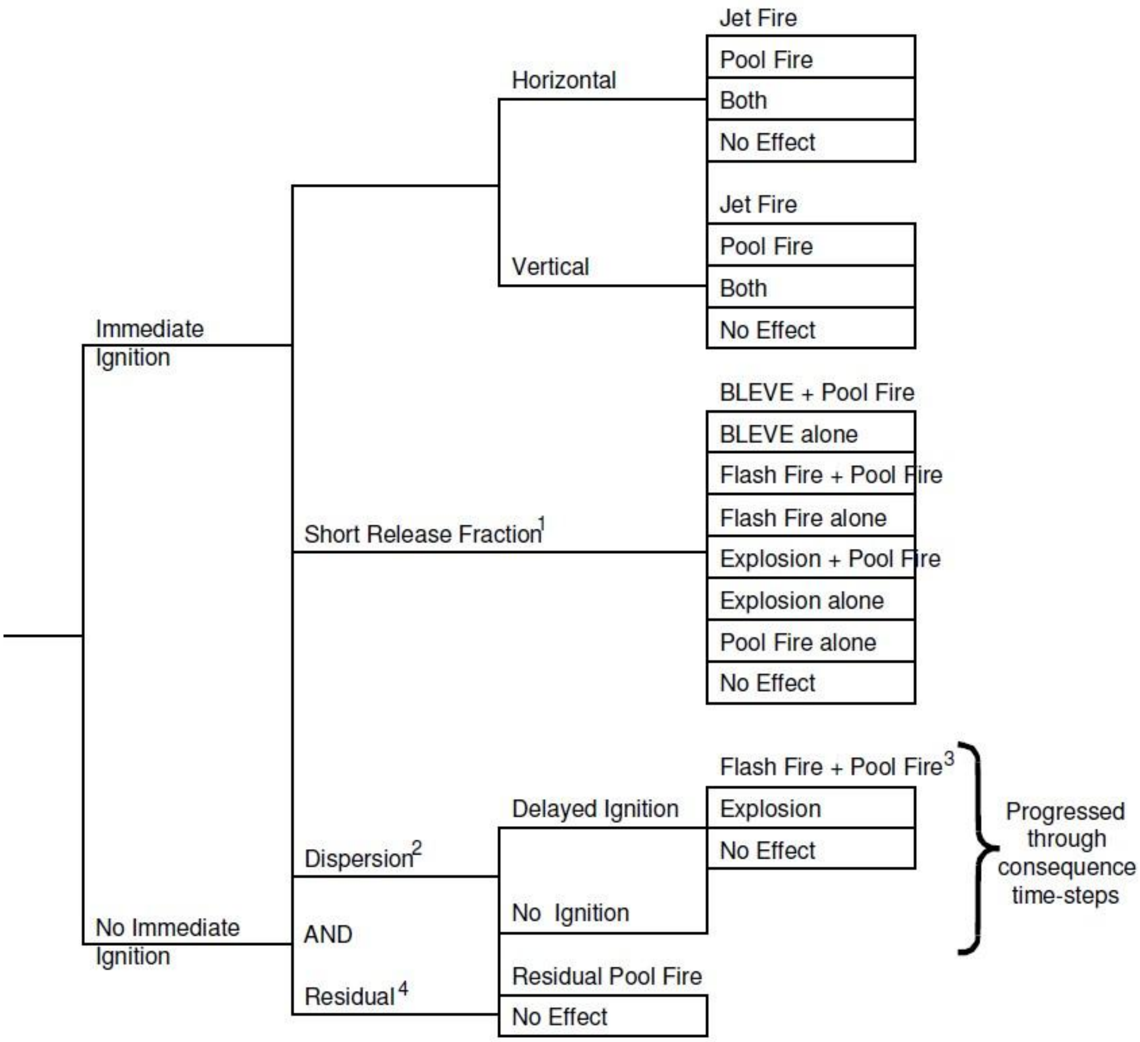

Figure 29. PHAST Risk consequence event trees for a continuous release with liquid rainout.[43]

4 Release Scenario Frequencies

Several accidental release scenarios were analyzed using the PHAST Risk software for each phase of LNG ISO tank container 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. The following section will provide the model conditions for each scenario and discuss the event trees used to estimate the release frequencies.

The LNG ISO tank container operations were grouped into three separate categories, distinguished by the type of operations and the unique risks present:

1. Lift On at intermodal facility in Hialeah Yard and yard movement.
2. Main line movement (Route 1, 2, or 3).

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[43] PHAST Risk Technical Documentation, "MPACT Theory," DNV Software, page 52 (2010).

3. Yard movement and Lift Off at destination intermodal facility.

(b)

For all three operations categories, the ISOs are assumed to have an LNG capacity of (b) (4) gallons, and it is expected to be handled at its boiling point temperature (-223°F/-142°C) at the design pressure of psig pressure. The ½-inch and 2-inch hole size scenarios conservatively assumed a constant leak source pressure of (4) (b) psig at the saturation temperature of methane; it was assumed that the LNG was released at this same pressure and temperature for the (4) 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 six feet, and all releases were assumed to be directed horizontally to conservatively maximize the flammable vapor dispersion distance.

4.1 LNG ISO Container Lifting Accidents

The LNG ISOs will be lifted onto well cars at Hialeah Yard intermodal facility and lifted off at the destination facility. The ISOs will be lifted by rubber tire gantry cranes or a container handler depending on the facility and the logistics for each train.

(b)
(4)

Based on the assumed daily movement of (b) ISO containers, the analysis accounted for (b) lifts per day at Hialeah Yard, and another (b) lifts per day at the receiving intermodal facility. The (4) (4) frequency for dropping an ISO that results in a 50 mm hole is 6.7×10(4) $^{-7}$ per lift (see Section 3.1). For (b) lifts per day, this results in an LOC frequency of [redacted]^{1} for Hialeah and for each destination intermodal facility. The event frequency is provided in Table 30. (4)

Table 30. LOC frequency for dropping an LNG ISO container at an intermodal facility.

Event	Release Frequency
Large leak (50 mm)	(b) (4) [redacted] [redacted]

4.2 Train Movement Accidents in Intermodal Facilities and Rail Yards

ISOs in well cars will be moved along intermodal ramps and within rail yards during train assembly and movement. Because the speed limits, rail quality, and adjacent activities differ between the yard line and the mainline, the yards and intermodal facilities were considered separately from the mainline in this QRA.

Given the fact that intermodal cars are intended to be moved as freight out of the yards, each ISO-containing train was assumed to travel the entire length of the intermodal facility/yard once each day. Using this uniform basis, a general event tree represents the frequency for all releases involving from one to four cars in any yard.[44]

The event frequencies for each release source size in a yard are summarized from the event tree as shown in Table 31, and the full event tree demonstrating the calculation of individual event frequencies is shown in Figure 30. Note that the event frequencies and event tree correspond to train Configuration 1 (C-1) only. Event trees representing the yard movements for the remaining train configurations are provided in Appendix D.

Table 31. Event frequencies for LNG ISO yard movement release scenarios at yards and intermodal facilities, presented here for Configuration 1 (C-1).[45]

	Release rate (kg/s)	Release Frequency (/year)
1 of (b [redacted] ISOs Involved)	0	1.68×10^{-4}
	1.17	2.46×10^{-6}
	18.8	4.40×10^{-6}
	Catastrophic Rupture (1 ISO)	5.28×10^{-7}
2 of (b [redacted] ISOs Involved)	0	1.44×10^{-4}
	1.57	4.23×10^{-6}
	19.4	7.61×10^{-6}
	37.6	9.78×10^{-8}
	Catastrophic Rupture (1 ISO)	9.36×10^{-7}
	Catastrophic Rupture (2 ISOs)	1.41×10^{-9}
3 of (b [redacted] ISOs Involved)	0	1.47×10^{-4}
	2.01	6.53×10^{-6}
	20.0	1.18×10^{-5}
	40.8	3.07×10^{-7}
	Catastrophic Rupture (1 ISO)	1.49×10^{-6}
	Catastrophic Rupture (2 ISOs)	4.49×10^{-9}
4 of (b [redacted] ISOs Involved)	0	4.66×10^{-4}
	2.51	2.78×10^{-5}
	20.6	5.08×10^{-5}
	38.8	1.96×10^{-6}
	59.0	3.38×10^{-8}
	Catastrophic	6.58×10^{-6}

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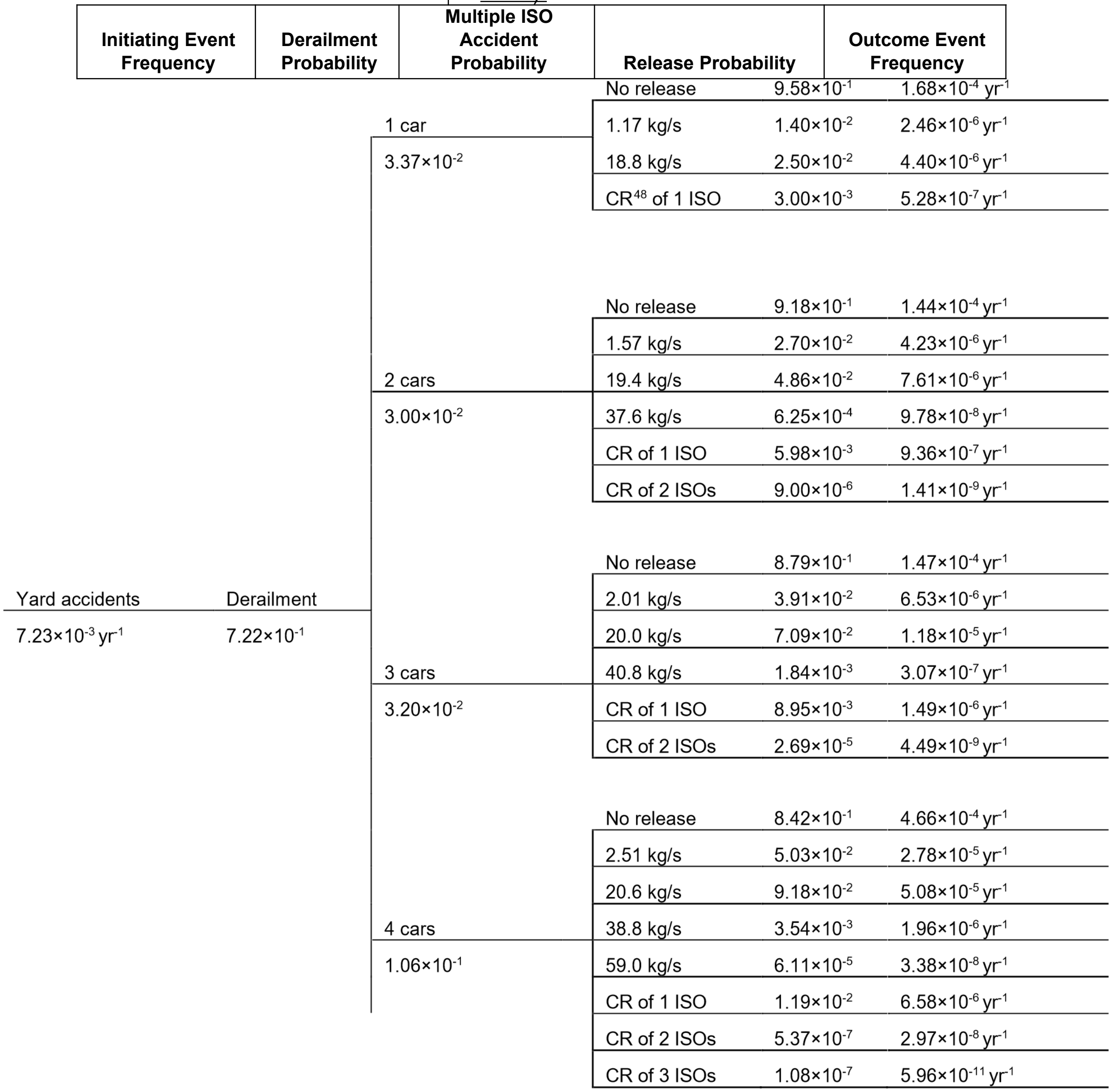
[44] The derailment probability analysis described in Section 3.1.3 determined that, on average, 4 rail cars derail in the event of an accident with derailment in yards.

[45] C-1 references the train configuration where all (b [redacted] LNG ISO cars are in a row, starting at train position (b) [redacted] See Section 3.1.3 for a detailed explanation of all configurations explored.) (4)

	Rupture (1 ISO)	
	Catastrophic Rupture (2 ISOs)	2.97×10^{-8}
	Catastrophic Rupture (3 ISOs)	5.96×10^{-11}



Initiating Event Frequency	Derailment Probability	Multiple ISO Accident Probability	Release Probability		Outcome Event Frequency
Yard accidents 7.23×10^{-3} yr^{-1}	Derailment 7.22×10^{-1}	1 car 3.37×10^{-2}	No release	9.58×10^{-1}	1.68×10^{-4} yr^{-1}
			1.17 kg/s	1.40×10^{-2}	2.46×10^{-6} yr^{-1}
			18.8 kg/s	2.50×10^{-2}	4.40×10^{-6} yr^{-1}
			CR[48] of 1 ISO	3.00×10^{-3}	5.28×10^{-7} yr^{-1}
		2 cars 3.00×10^{-2}	No release	9.18×10^{-1}	1.44×10^{-4} yr^{-1}
			1.57 kg/s	2.70×10^{-2}	4.23×10^{-6} yr^{-1}
			19.4 kg/s	4.86×10^{-2}	7.61×10^{-6} yr^{-1}
			37.6 kg/s	6.25×10^{-4}	9.78×10^{-8} yr^{-1}
			CR of 1 ISO	5.98×10^{-3}	9.36×10^{-7} yr^{-1}
			CR of 2 ISOs	9.00×10^{-6}	1.41×10^{-9} yr^{-1}
		3 cars 3.20×10^{-2}	No release	8.79×10^{-1}	1.47×10^{-4} yr^{-1}
			2.01 kg/s	3.91×10^{-2}	6.53×10^{-6} yr^{-1}
			20.0 kg/s	7.09×10^{-2}	1.18×10^{-5} yr^{-1}
			40.8 kg/s	1.84×10^{-3}	3.07×10^{-7} yr^{-1}
			CR of 1 ISO	8.95×10^{-3}	1.49×10^{-6} yr^{-1}
			CR of 2 ISOs	2.69×10^{-5}	4.49×10^{-9} yr^{-1}
		4 cars 1.06×10^{-1}	No release	8.42×10^{-1}	4.66×10^{-4} yr^{-1}
			2.51 kg/s	5.03×10^{-2}	2.78×10^{-5} yr^{-1}
			20.6 kg/s	9.18×10^{-2}	5.08×10^{-5} yr^{-1}
			38.8 kg/s	3.54×10^{-3}	1.96×10^{-6} yr^{-1}
			59.0 kg/s	6.11×10^{-5}	3.38×10^{-8} yr^{-1}
			CR of 1 ISO	1.19×10^{-2}	6.58×10^{-6} yr^{-1}
			CR of 2 ISOs	5.37×10^{-7}	2.97×10^{-8} yr^{-1}
			CR of 3 ISOs	1.08×10^{-7}	5.96×10^{-11} yr^{-1}

Figure 30. Event tree for yard movement for train Configuration 1 (C-1). “Outcome Event Frequency” is the product of the “Initiating Event Frequency,” “Derailment Probability,” “Multiple ISO Accident Probability,” and “Release Probability.”

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[48] The abbreviation “CR” represents a catastrophic rupture where the entire (b) (4) gallons contained in the ISO is released instantaneously.

4.3 Train Accidents on the Mainline and Port Lead Tracks

ISOs in well cars will be moved on mainline track from Hialeah Yard to either port lead tracks or to Bowden Yard in Jacksonville. The port lead tracks are treated here equivalently to mainline tracks. The QRA assumes that each route is independent and handles (b) ISOs per day of LNG. (4)

Event trees representing the three separate routes, multiple mainline train speeds, and multiple train configurations are provided in Appendix D. The following tables summarize the release rates and associated release frequencies for combinations of one to ten ISOs along each route for train Configuration 1 (C-1) and mainline train movement at train speeds between 25 mph and 60 mph.[46] 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 ISO Accident Probability,” and “Release Probability.”

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[46] C-1 references the train configuration where all (b LNG ISO cars are in a row, starting at train position (b) See Section 3.1.3 for a detailed explanation of all configurations explored.) (4)

Table 32. Event frequencies for LNG ISO mainline movement release scenarios along Route 1 (Hialeah to Port of Miami), presented here for Configuration 1 (C-1) and train speeds between 25 mph and 60 mph.

Release rate (kg/s)	Release Frequency (/year)	Release rate (kg/s)	Release Frequency (/year)	Release rate (kg/s)	Release Frequency (/year)
1 of (b ISOs Involved		6 of (b ISOs Involved		9 of (b ISOs Involved	
0	1.28×10^{-3}	0	1.69×10^{-4}	0	1.30×10^{-4}
1.17	1.87×10^{-5}	3.58	1.53×10^{-5}	5.30	1.82×10^{-5}
18.8	3.34×10^{-5}	21.7	2.84×10^{-5}	23.5	3.43×10^{-5}
CR[50] 1 ISO	4.01×10^{-6}	39.9	1.82×10^{-6}	41.7	3.53×10^{-6}
2 of (b ISOs Involved		58.1	6.26×10^{-8}	59.9	2.12×10^{-7}
0	2.74×10^{-4}	76.4	1.21×10^{-9}	78.1	8.18×10^{-9}
1.57	8.07×10^{-6}	CR 1 ISO	3.87×10^{-6}	96.3	2.10×10^{-10}
19.4	1.45×10^{-5}	CR 2 ISOs	2.91×10^{-8}	CR 1 ISO	5.05×10^{-6}
37.6	1.87×10^{-7}	CR 3 ISOs	1.17×10^{-10}	CR 2 ISOs	6.08×10^{-8}
CR 1 ISO	1.79×10^{-6}	7 of (b ISOs Involved		CR 3 ISOs	4.27×10^{-10}
CR 2 ISOs	2.69×10^{-9}	0	1.47×10^{-4}	10 of (b ISOs Involved	
3 of (b ISOs Involved		4.14	1.57×10^{-5}	0	1.23×10^{-4}
0	2.59×10^{-4}	22.3	2.93×10^{-5}	5.88	1.92×10^{-5}
2.01	1.15×10^{-5}	40.5	2.26×10^{-6}	24.1	3.66×10^{-5}
20.0	2.09×10^{-5}	58.7	9.70×10^{-8}	42.3	4.24×10^{-6}
40.8	5.41×10^{-7}	76.9	2.50×10^{-9}	60.5	2.91×10^{-7}
CR 1 ISO	2.63×10^{-6}	95.1	3.85×10^{-11}	78.7	1.31×10^{-8}
CR 2 ISOs	7.93×10^{-9}	CR 1 ISO	4.10×10^{-6}	96.9	4.04×10^{-10}
4 of (b ISOs Involved		CR 2 ISOs	3.70×10^{-8}	CR 1 ISO	5.52×10^{-6}
0	2.05×10^{-4}	CR 3 ISOs	1.86×10^{-10}	CR 2 ISOs	7.48×10^{-8}
2.51	1.22×10^{-5}	8 of (b ISOs Involved		CR 3 ISOs	6.00×10^{-10}
20.6	2.23×10^{-5}	0	1.33×10^{-4}		
38.8	8.61×10^{-7}	4.77	1.98×10^{-5}		
59.0	1.49×10^{-8}	22.9	3.07×10^{-5}		
CR 1 ISO	2.89×10^{-6}	41.1	2.77×10^{-6}		
CR 2 ISOs	1.30×10^{-8}	59.3	1.42×10^{-7}		
CR 3 ISOs	2.62×10^{-11}	77.5	4.58×10^{-9}		
5 of (b ISOs Involved		95.7	9.42×10^{-11}		
0	1.38×10^{-4}	CR 1 ISO	4.41×10^{-6}		
3.03	1.04×10^{-5}	CR 2 ISOs	4.64×10^{-8}		
21.1	1.91×10^{-5}	CR 3 ISOs	2.79×10^{-10}		
39.4	9.84×10^{-7}				
57.6	2.53×10^{-8}				
77.4	3.27×10^{-10}				
CR 1 ISO	2.54×10^{-6}				
CR 2 ISOs	1.53×10^{-8}				
CR 3 ISOs	4.60×10^{-11}				

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[50] The abbreviation "CR" represents a catastrophic rupture where the entire (b) (4) gallons contained in the ISO is released instantaneously.

Table 33. Event frequencies for LNG ISO mainline movement release scenarios along Route 2 (Hialeah to Port Everglades), presented here for Configuration 1 (C-1) and train speeds between 25 mph and 60 mph.

Release rate (kg/s)	Release Frequency (/year)
1 of (b ISOs Involved	
0	2.93×10^{-3}
1.17	3.49×10^{-5}
18.8	6.23×10^{-5}
CR[51] 1 ISO	7.48×10^{-6}
2 of (b ISOs Involved	
0	5.11×10^{-4}
1.57	1.51×10^{-5}
19.4	2.71×10^{-5}
37.6	3.48×10^{-7}
CR 1 ISO	3.33×10^{-6}
CR 2 ISOs	5.02×10^{-9}
3 of (b ISOs Involved	
0	4.83×10^{-4}
2.01	2.15×10^{-5}
20.0	3.90×10^{-5}
40.8	1.01×10^{-6}
CR 1 ISO	4.92×10^{-6}
CR 2 ISOs	1.48×10^{-8}
4 of (b ISOs Involved	
0	3.82×10^{-4}
2.51	2.28×10^{-5}
20.6	4.17×10^{-5}
38.8	1.61×10^{-6}
59.0	2.77×10^{-8}
CR 1 ISO	5.39×10^{-6}
CR 2 ISOs	2.43×10^{-8}
CR 3 ISOs	4.88×10^{-11}
5 of (b ISOs Involved	
0	2.58×10^{-4}
3.03	1.94×10^{-5}
21.1	3.57×10^{-5}
39.4	1.84×10^{-6}
57.6	4.72×10^{-8}
77.4	6.10×10^{-10}
CR 1 ISO	4.74×10^{-6}
CR 2 ISOs	2.85×10^{-8}
CR 3 ISOs	8.59×10^{-11}
6 of (b ISOs Involved	
0	3.15×10^{-4}
3.58	2.86×10^{-5}
21.7	5.30×10^{-5}
39.9	3.41×10^{-6}
58.1	1.17×10^{-7}
76.4	2.25×10^{-9}
CR 1 ISO	7.22×10^{-6}
CR 2 ISOs	5.43×10^{-8}
CR 3 ISOs	2.18×10^{-10}
7 of (b ISOs Involved	
0	2.75×10^{-4}
4.14	2.94×10^{-5}
22.3	5.48×10^{-5}
40.5	4.22×10^{-6}
58.7	1.81×10^{-7}
76.9	4.66×10^{-9}
95.1	7.19×10^{-11}
CR 1 ISO	7.65×10^{-6}
CR 2 ISOs	6.9170×10^{-8}
CR 3 ISOs	3.46×10^{-10}
8 of (b ISOs Involved	
0	2.48×10^{-4}
4.77	3.70×10^{-5}
22.9	5.74×10^{-5}
41.1	5.16×10^{-6}
59.3	2.66×10^{-7}
77.5	8.54×10^{-9}
95.7	1.76×10^{-10}
CR 1 ISO	8.22×10^{-6}
CR 2 ISOs	8.66×10^{-8}
CR 3 ISOs	5.21×10^{-10}
9 of (b ISOs Involved	
0	2.34×10^{-4}
5.30	3.39×10^{-5}
23.5	6.41×10^{-5}
41.7	6.59×10^{-6}
59.9	3.96×10^{-7}
78.1	1.53×10^{-8}
96.3	3.93×10^{-10}
CR 1 ISO	9.42×10^{-6}
CR 2 ISOs	1.13×10^{-7}
CR 3 ISOs	7.96×10^{-10}
10 of (b ISOs Involved	
0	2.30×10^{-4}
5.88	3.59×10^{-5}
24.1	6.83×10^{-5}
42.3	7.91×10^{-6}
60.5	5.42×10^{-7}
78.7	2.44×10^{-8}
96.9	7.54×10^{-10}
CR 1 ISO	1.03×10^{-5}
CR 2 ISOs	1.40×10^{-7}
CR 3 ISOs	1.12×10^{-9}

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[51] The abbreviation "CR" represents a catastrophic rupture where the entire (b) (4) gallons contained in the ISO is released instantaneously.

Table 34. Event frequencies for LNG ISO mainline movement release scenarios along Route 3 (Hialeah to Bowden Yard), presented here for Configuration 1 (C-1) and train speeds between 25 mph and 60 mph.

Release rate (kg/s)	Release Frequency (/year)
1 of (b ISOs Involved	
0	3.11×10^{-2}
1.17	4.54×10^{-4}
18.8	8.10×10^{-4}
CR[52] 1 ISO	9.72×10^{-5}
2 of (b ISOs Involved	
0	6.65×10^{-3}
1.57	1.96×10^{-4}
19.4	3.52×10^{-4}
37.6	4.53×10^{-6}
CR 1 ISO	4.33×10^{-5}
CR 2 ISOs	6.52×10^{-8}
3 of (b ISOs Involved	
0	6.28×10^{-3}
2.01	2.80×10^{-4}
20.0	5.06×10^{-4}
40.8	1.31×10^{-5}
CR 1 ISO	6.39×10^{-5}
CR 2 ISOs	1.92×10^{-7}
4 of (b ISOs Involved	
0	4.97×10^{-3}
2.51	2.97×10^{-4}
20.6	5.42×10^{-4}
38.8	2.09×10^{-5}
59.0	3.61×10^{-7}
CR 1 ISO	7.01×10^{-5}
CR 2 ISOs	3.17×10^{-7}
CR 3 ISOs	6.35×10^{-10}
5 of (b ISOs Involved	
0	3.36×10^{-3}
3.03	2.52×10^{-4}
21.1	4.64×10^{-4}
39.4	2.39×10^{-5}
57.6	6.14×10^{-7}
77.4	7.94×10^{-9}
CR 1 ISO	6.16×10^{-5}
CR 2 ISOs	3.71×10^{-7}
CR 3 ISOs	1.12×10^{-9}
6 of (b ISOs Involved	
0	4.09×10^{-3}
3.58	3.72×10^{-4}
21.7	6.89×10^{-4}
39.9	4.43×10^{-5}
58.1	1.52×10^{-6}
76.4	2.93×10^{-8}
CR 1 ISO	9.38×10^{-5}
CR 2 ISOs	7.06×10^{-7}
CR 3 ISOs	2.83×10^{-9}
7 of (b ISOs Involved	
0	3.57×10^{-3}
4.14	3.82×10^{-4}
22.3	7.12×10^{-4}
40.5	5.49×10^{-5}
58.7	2.35×10^{-6}
76.9	6.06×10^{-8}
95.1	9.34×10^{-10}
CR 1 ISO	9.95×10^{-5}
CR 2 ISOs	8.98×10^{-7}
CR 3 ISOs	4.50×10^{-9}
8 of (b ISOs Involved	
0	3.23×10^{-3}
4.77	4.81×10^{-4}
22.9	7.46×10^{-4}
41.1	6.71×10^{-5}
59.3	3.45×10^{-6}
77.5	1.11×10^{-7}
95.7	2.28×10^{-9}
CR 1 ISO	1.07×10^{-4}
CR 2 ISOs	1.13×10^{-6}
CR 3 ISOs	6.78×10^{-9}
9 of (b ISOs Involved	
0	3.16×10^{-3}
5.30	4.41×10^{-4}
23.5	8.33×10^{-4}
41.7	8.57×10^{-5}
59.9	5.14×10^{-6}
78.1	1.98×10^{-7}
96.3	5.10×10^{-9}
CR 1 ISO	1.22×10^{-4}
CR 2 ISOs	1.47×10^{-6}
CR 3 ISOs	1.04×10^{-8}
10 of (b ISOs Involved	
0	2.99×10^{-3}
5.88	4.66×10^{-4}
24.1	8.88×10^{-4}
42.3	1.03×10^{-4}
60.5	7.05×10^{-6}
78.7	3.17×10^{-7}
96.9	9.80×10^{-9}
CR 1 ISO	1.34×10^{-4}
CR 2 ISOs	1.81×10^{-6}
CR 3 ISOs	1.46×10^{-8}

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[52] The abbreviation "CR" represents a catastrophic rupture where the entire (b) (4) gallons contained in the ISO is released instantaneously.

5 Release Location Assumptions

The release scenarios can occur in one of the four yard locations, (1) Hialeah Yard, (2) Bowden Yard, (3) Port Everglades or (4) Port of Miami, or along any of the three proposed routes between these yards. This section provides descriptions of the assumptions for the release locations applied to each route.

5.1 Hialeah Yard Releases

The Hialeah Yard is located in Hialeah, Florida, approximately ten miles northwest of Miami. The Hialeah Yard represents the starting point for all three proposed routes and is the location where all LNG ISO containers will be loaded into the well cars. The Hialeah Yard contains two release scenario classifications: (1) ISO container lifting, and (2) yard movement. The lifting operations have been modeled as a fixed location release and as a release anywhere along the intermodal ramp track, while the yard movement scenario follows a path which terminates at the approximate FECR yard boundaries. The spur track connecting to the neighboring LNG facility to the north was also considered. The QRA transitioned to mainline accident analysis outside of these boundaries. Further, the layout of the Hialeah yard, which is enclosed on the east side by an approximately 10 ft high wall, will reduce the likelihood that flammable vapor clouds will expand beyond the property in that direction.[47] Thus, the route of the train was modeled for the primary north-south track on the west side of the property. PHAST Risk modeled the release sources for the route at 75-feet intervals along the path.

Two route representations were applied for the Hialeah Yard to demonstrate the range of risk results applicable to lifting and train movement for the intermodal facilities and rail yards. The first route assumption is depicted in the aerial image of the Hialeah Yard in Figure 31. This model represents all lifting activities as occurring at a single point on the intermodal ramp and train movement located only on the western-most track in the yard. As will be shown in the results section, these assumptions lead to the maximum calculated distance to IR risk thresholds for lifting operations but only negligibly affect the distance to the thresholds for train movement. The second route assumption is depicted in the aerial image in Figure 32. This second model represents lifting along the entire eastern intermodal ramp track and train movements down the eastern track, the circular turnaround at the south end of the facility, and the western-most track. The effects of these assumed routes on the calculated risk will be discussed in the Results section.

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[47] Note that the integral equation-based models in PHAST Risk are not suitable for modeling the barrier effects of walls on flammable vapor cloud dispersion; thus, the north-south track was used as the primary rail yard route.

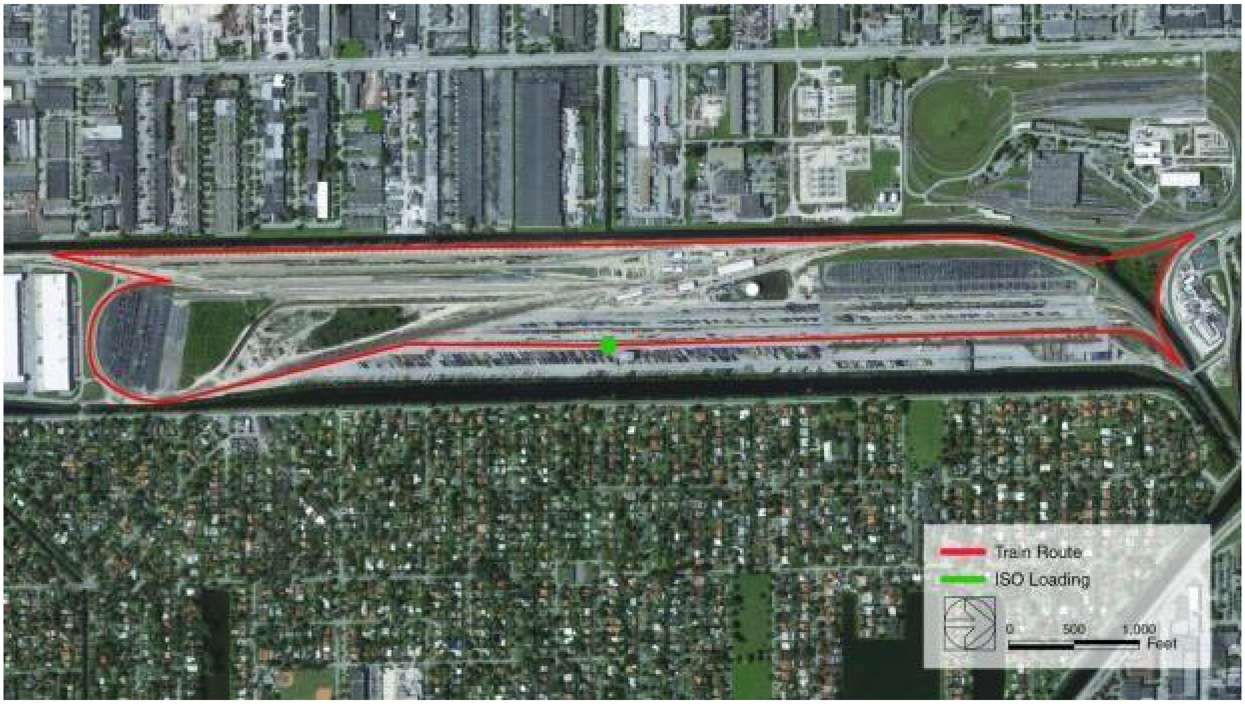

Figure 31. Aerial view of the Hialeah Yard. The train route along the outside yard rail lines is red and a representative location of lifting operations is shown as a green dot.

Figure 32. Aerial view of the Hialeah Yard. The train route through the yard is red and the range of lifting operations along the intermodal ramp is shown as a green line.

5.2 Port of Miami Intermodal Facility Releases

The Port of Miami intermodal facility is located on Dodge Island in Biscayne Bay, and is the destination yard for all LNG ISO containers on Route 1. The Port of Miami intermodal facility contains two release scenario classifications: (1) ISO container lifting, and (2) yard movement.

Figure 33 shows an aerial image of the Port of Miami intermodal facility depicting the location of the lifting activities as a point and the yard rail line. The QRA transitioned to mainline accident analysis outside of these boundaries. PHAST Risk modeled the release sources for the yard track route at 75-feet intervals along the path.

Figure 33. Aerial view of Port of Miami. The yard rail line is red and the approximate location of lifting operations is represented as a green dot.

5.3 Port Everglades Intermodal Facility Releases

The FECR Port Everglades intermodal facility is located directly to the east of Fort Lauderdale airport in Port Everglades, Florida. The Port Everglades intermodal facility is the destination point for Route 2, and as such, all LNG ISOs on this route will be lifted off the well cars here. Therefore, the Port Everglades intermodal facility contains two release scenario classifications:
(1) ISO container lifting, and (2) yard movement.

An aerial image of the Port Everglades intermodal facility, depicting the route for the release scenario, is provided in Figure 34. The train yard movement scenario follows a path which terminates at the approximate FECR property boundaries. The QRA transitioned to mainline accident analysis outside of these boundaries. PHAST Risk modeled the release sources for the route at 75-feet intervals along the path.

Figure 34. Aerial view of the Port Everglades intermodal facility. The yard rail line is red and the approximate location of lifting operations is represented as a green dot.

5.4 Bowden Yard Releases

The Bowden Yard is located on the south side of Jacksonville, Florida, and represents the northern terminus of the FECR mainline track considered in this QRA. The Bowden Yard contains two release scenario classifications: (1) ISO container lifting, and (2) yard movement. An aerial image of the Bowden Yard, depicting the location/routes for the two release scenarios, is provided in Figure 35. The lifting operations have been modeled as a fixed location release while the yard movement scenario follows a path which terminates at the approximate FECR property boundaries. PHAST Risk modeled the release sources for the route at 75-feet intervals along the path.

Figure 35. Aerial view of the Bowden Yard. The yard rail line is red and the approximate location of the lifting operations is represented as a green dot.

5.5 Route 1 – Hialeah to Port of Miami

Route 1 begins at Hialeah Yard and ends at the Port of Miami intermodal facility, as shown earlier in Figure 18. The majority of the route is covered by the FECR mainline. This population density is bounded by the mainline risk analysis. Mainline movement is the only release scenario classification considered along this 15-mile route. PHAST Risk modeled the release sources for the route at 75-feet intervals along the path.

5.6 Route 2 – Hialeah to Port Everglades

The second route begins at Hialeah Yard and ends at Port Everglades intermodal facility, as shown earlier in Figure 19. Nearly the entirety of the route is covered by the FECR mainline. Mainline movement is the only release scenario classification considered along this 28-mile route. PHAST Risk modeled the release sources for the route at 75-feet intervals along the path.

5.7 Route 3 – Hialeah to Bowden Yard

Route 3 is the longest of the three routes, starting at Hialeah Yard and terminating at the Bowden Yard, as shown earlier in Figure 20. Mainline movement is the only release scenario classification considered along this 364-mile route. PHAST Risk modeled the release sources for the route at 75-feet intervals along the path.

6 Potentially Affected Populations

The population along the rail routes and around the rail yards and intermodal facilities directly affect the risk; thus, the population was evaluated as part of the QRA. A commercially available mapping tool, ArcGIS (ArcMap v10.2.1), along with commercially available census and rail databases, were used to estimate the nearby populations for the Hialeah Yard, Port Everglades, Port of Miami, Bowden Yard, and the FECR mainline rail and lead tracks to both Port Everglades and Port of Miami. By using ArcGIS, 2010 U.S. census data,[48] 2012 railroads geographic data,[49] and satellite imagery for the state of Florida, a multilayered GIS map was generated. The rail map layer was then filtered to exclude all non-FECR[50] railroads and census data was filtered to exclude all census blocks that did not intersect an area of 1.6 miles (2500 m) on either side of the FECR rail line.

6.1 Hialeah Yard Populations

Analysis of the Hialeah Yard's surrounding population was accomplished by defining the Hialeah Yard track in GIS rail map layer and excluding all other rail lines. Subsequently, a query of the census layer data was run to identify only the relevant census blocks that were within 1.6 miles (2500 m) of the specified yard track. The results of this map query identified 1,105 census blocks that were within 1.6 miles (2500 m) to either side of the approximate location of the yard line track. Finally, using geographical markers, such as highways and major roads, the resulting census map was grouped into four consolidated census blocks.

The population densities of the four larger consolidated census blocks represent an average population density for all of the census blocks contained within each. The consolidated census block population densities were directly used in the QRA analysis. An aerial view of the Hialeah Yard and four consolidated census blocks is depicted in Figure 36. A table of the population densities of the four consolidated census block is provided in Table 35.

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[48] Florida Geographic Data Library (FGDL) http://www.fgdl.org, March 11, 2010.

[49] Florida Geographic Data Library (FGDL) http://www.fgdl.org, 2012.

[50] As labeled in the FGDL 2012 railroad shapefile.

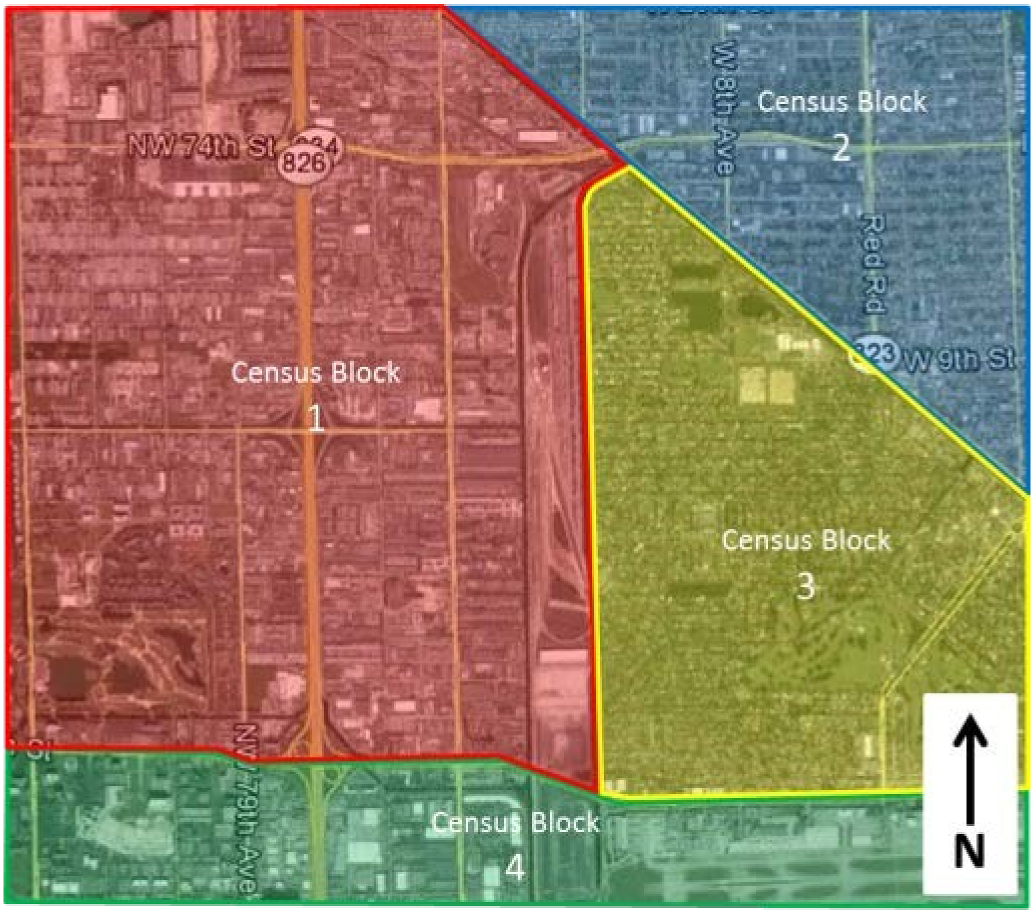

Figure 36. Aerial view of the Hialeah Yard depicting the four consolidated census blocks used to represent nearby populations.

Table 35. Population densities of the consolidated census blocks in the Hialeah Yard area.

Census Block	Population Description	Population Density (People per square mile)
1	Commercial / Industrial	1,276
2	Residential	12,860
3	Residential	5,471
4	Commercial / Industrial	447

6.2 Port of Miami Populations

The census data used to determine population density is based on residential populations. As Port of Miami is located on an island dedicated to the port operations, the census data was not applicable. In addition to general port operations, the Port of Miami contains seven cruise terminals, each of which processes thousands of passengers and crew members per year. As such, the population analysis also considered cruise ship passengers and crew, port operations personnel, and surrounding residential islands.

In 2015, the Port of Miami processed nearly 4.9 million cruise passengers,[51] equating to approximately 13,500 passengers per day. Based on Carnival cruise ship capacity information, crew numbers are on average 40% of the number of passengers,[52] therefore, it was assumed that there are approximately 19,000 passengers and crew present at the cruise terminals each day. The 19,000 people were conservatively assumed to be present for 24 hours, even though embarkation and disembarkation would not take an entire day. For example, the cruise operations may only lead to high population for a few hours a day. Thus, by assuming the maximum population is present for 24 hours per day, the potentially affected population is conservatively maximized to conservatively upper bound the risk. This population was allocated to the region labelled Area A in Figure 37.

During 2013 and 2014, Port of Miami had 349 full time employees;[53] this population was assigned to Area B as shown in Figure 37 in the QRA model. The population density for the residential areas, labelled Area C in Figure 37, was calculated from the census data as per the Port of Miami Lead Track section. The populations for the three areas are summarized in Table 36.

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[51] Port of Miami, *Cruise Facts*, http://www.miamidade.gov/portmiami/cruise-facts.asp.

[52] Carnival, *Cruise Ships*, http://www.carnival.com/cruise-ships.aspx.

[53] Miami-Dade Seaport Department, *Comprehensive Annual Financial Reports for the fiscal years ended September 30, 2014 and 2013*, http://www miamidade.gov/portmiami/library/reports/comprehensive-annualfinancial-report-2014.pdf.

Figure 37. Aerial view of the Port of Miami depicting the three distinct population densities.

Table 36. Population of the consolidated census blocks in the Port of Miami area.

Area	Population Description	Population (People per Block)	Population Density (People per square mile)
A	Cruise Ship	19,000	191,800
B	Industrial	350	488
C	Residential	--	10,252

6.3 Port Everglades Populations

Analysis of the Port Everglades intermodal facility was accomplished by defining the yard track in the GIS rail map layer and filtering all other track segments. Subsequently, a query of the census layer data was run to identify only the relevant census blocks that were within 1.6 miles (2500 m) of either side of the yard track. Finally, using geographical markers, such as a waterfront and highways, the resulting census map was grouped into four consolidated census blocks.

The population densities of the four larger consolidated census blocks represent an average population density for all of the census blocks contained within each. The consolidated census block population densities were directly used in the QRA analysis. An aerial view of the Port Everglades intermodal facility and four consolidated census blocks is depicted in Figure 38 and the corresponding population densities of the four blocks are provided in Table 37.

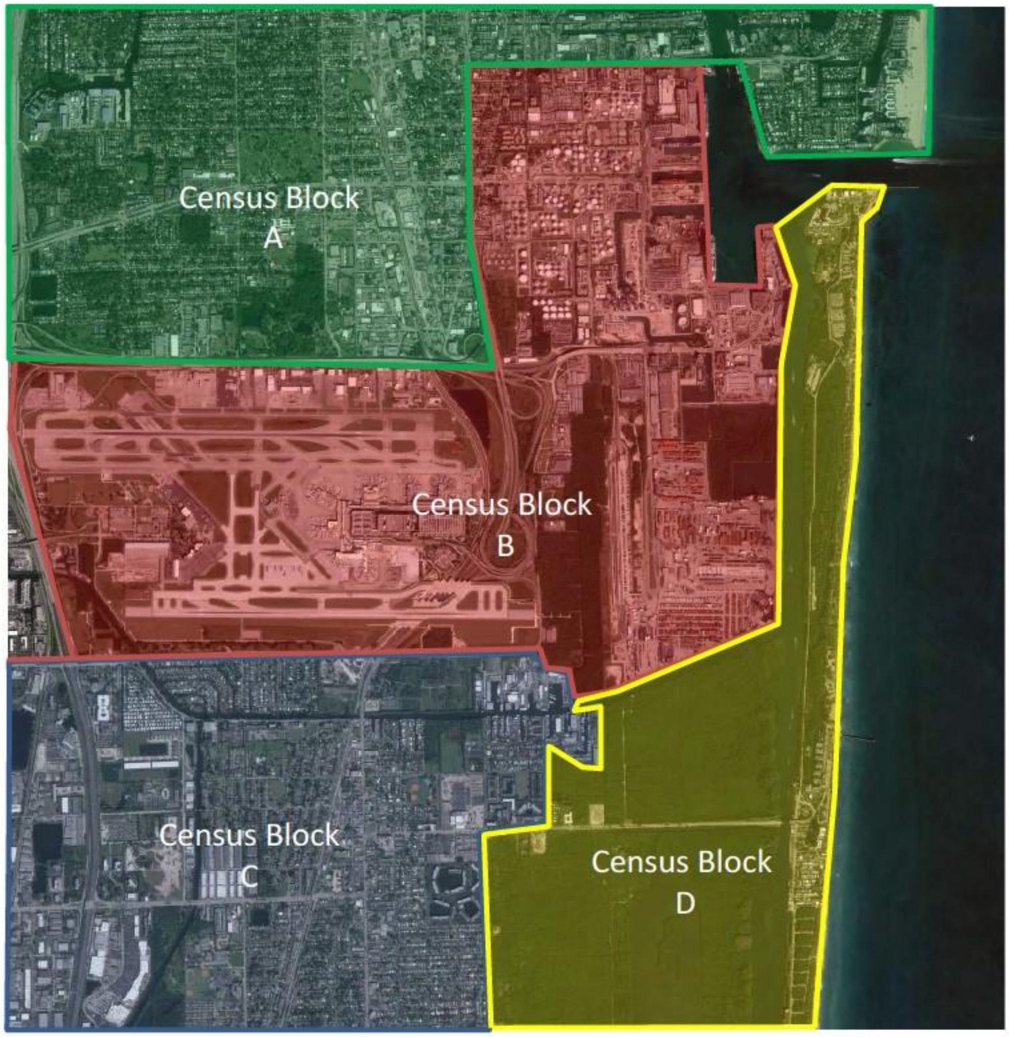

Figure 38. Aerial view of the Port Everglades intermodal facility depicting the four distinct population densities.

Table 37. Population densities of the consolidated census blocks in the Port Everglades intermodal facility area.

Census Block	Population Description	Population Density (People per square mile)
A	Residential / Commercial	4,680
B	Commercial / Industrial	707
C	Residential / Commercial	6,965
D	Sparse	250[60]

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[60] Based on the census data the population density for this area is zero, therefore 250 was chosen as a conservative assumption to account for recreational users of the parklands and waterways.

6.4 Bowden Yard Populations

Analysis of the Bowden Yard was accomplished by applying the census layer data for the relevant census blocks that were within 1.6 miles (2500 m) of either side of the locomotive turnaround track. The results of this map query identified 257 census blocks that were within 1.6 miles (2500 m) of either side of the yard track. Finally, using geographical markers, such as a waterfront and highways, the resulting census map was grouped into five consolidated census blocks.

The population densities of the four larger consolidated census blocks represent an average population density for all of the census blocks contained within each. The consolidated census block population densities were directly used in the QRA analysis. An aerial view of the Bowden Yard and five consolidated census blocks is depicted in Figure 39. A table of the population densities of the five consolidated census block is provided in Table 38.

Figure 39. Aerial view of the Bowden Yard depicting the five consolidated census blocks used to represent nearby populations.

Table 38. Population densities of the consolidated census blocks for the Bowden Yard.

Census Block	Population Description	Population Density (People per square mile)
A	Residential	2,847
B	Residential / Commercial	5,720
C	Residential	5,098
D	Commercial / Industrial	478
E	Residential / Commercial	687

6.5 Main Line Track Populations

Analysis of the longest section of mainline route from the Bowden rail yard to the Hialeah Yard was accomplished by filtering all sections of the FECR rail line (from the GIS rail map layer) to include only the rail sections from the approximate southern boundary of the Bowden Yard to the approximate northern boundary of the Hialeah Yard. A query of the census layer data was run to identify only the relevant census blocks that were within 1.6 miles (2500 m) of either side of the rail line. The results of this map query identified 37,837 census blocks that met the criterion. The routes to the Port of Miami and Port Everglades intermodal facilities are largely covered by this analysis, except for the individual port lead tracks.

The mainline census blocks were then grouped into one latitudinal-mile sections (north to south) along the rail line resulting in 314 consolidated census blocks. These consolidated census blocks, referred to here as "mile markers," represent the population per mile along the FECR mainline. The FECR mainline runs approximately north and south, but these mile markers are not the same as their rail mile markers.[54] The population densities of these 314 larger consolidated census blocks were directly used in the QRA analysis to represent the population along the rail line.

A plot showing the population density from the Bowden Yard (Mile Marker 1) to the Hialeah Yard (Mile Marker 314) is provided in Figure 40. The highest population densities are near the Hialeah Yard, which lies approximately ten miles northwest of Miami. The maximum population density was found at Mile Marker 308, with a population density of approximately 11,800 people/mile^2.

The population density profile is overlaid on an aerial image of the FECR rail line map, provided in Appendix E.

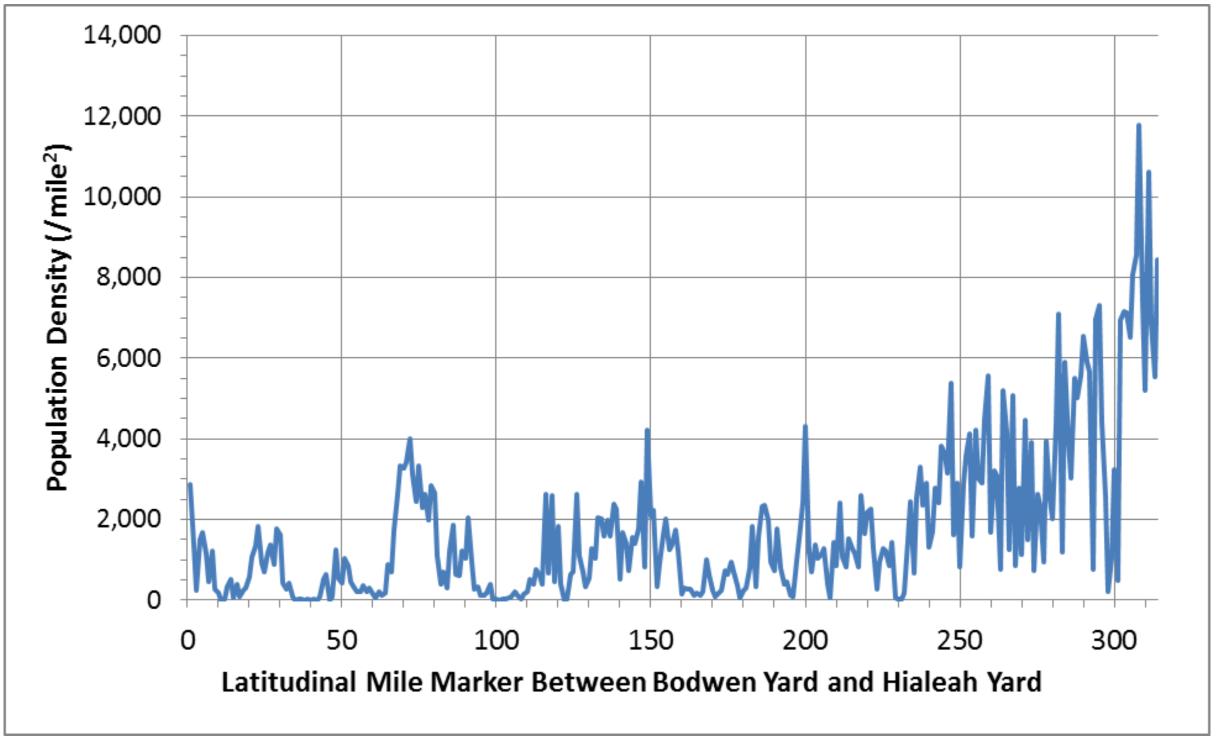

Figure 40. Average population density per latitudinal mile from the Bowden Yard to the

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[54] The mainline from Hialeah Yard to Bowden Yard is actually 364 miles long; however, by using latitude to estimate mile marker, the analysis resulted in 314 latitudinal miles which do not correspond to the FECR mile markers.

Hialeah Yard.

6.6 Port of Miami Lead Track Populations

The route between Hialeah Yard and Port of Miami was divided into three sections as shown in Figure 41. The population densities for Census Blocks 1 and 2 correspond to the population densities for mile markers 304-314 in Figure 40. For the Port of Miami lead track (census block 3), the census data for all census blocks within 1.6 miles (2500 m) of either side of the rail line were consolidated to calculate the population density for that portion of the track. The population densities for these Census Blocks are provided in Table 39. Therefore, the risk of transport along the Port of Miami lead track is bounded by the mainline track risk analysis with an average population density of 11,800 people/mile^2 at Mile Marker 308.

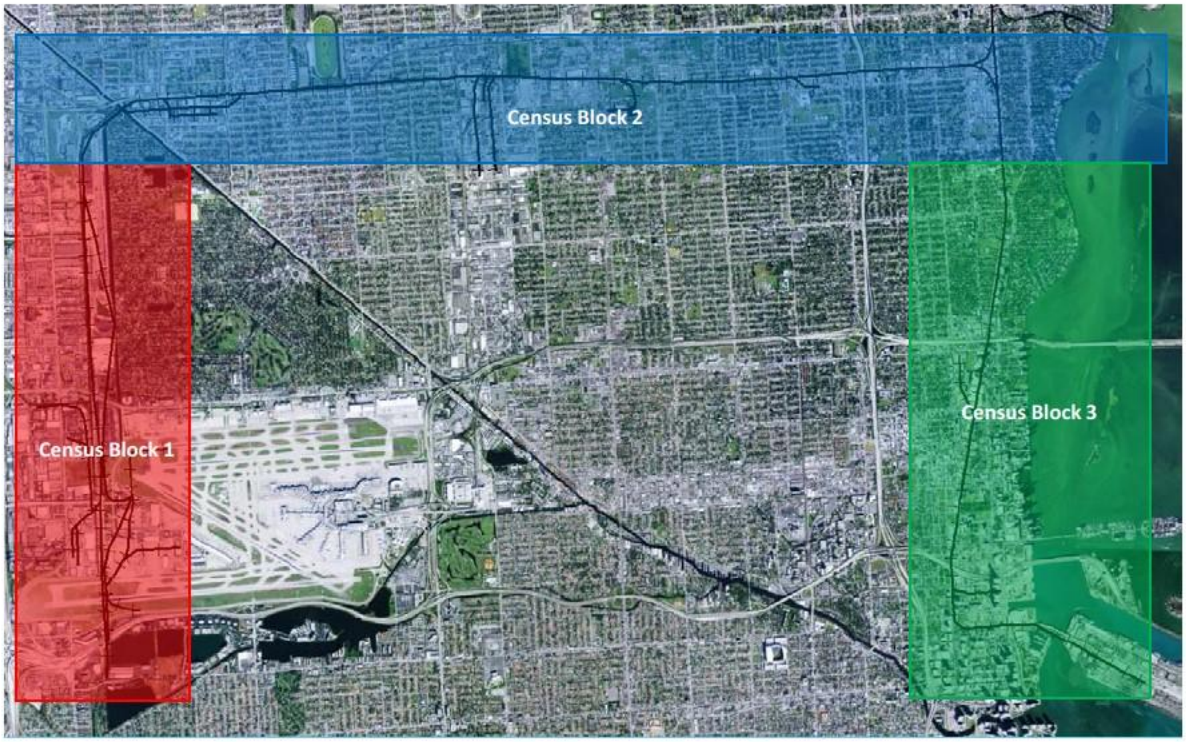

Figure 41. Aerial image of the route between Hialeah Yard and the Port of Miami.

Table 39. Population densities of the consolidated census blocks for Route 1.

Census Block	Population Description	Population Density (People per square mile)
1	Residential / Commercial	10,879
2	Residential / Commercial	11,069
3	Residential / Commercial	10,252

6.7 Port Everglades Lead Track Populations

The route from Hialeah Yard to Port Everglades initially follows the same track as the route to Bowden Yard, before turning onto the Port Everglades lead track, approximately 25 miles north on the mainline.

The population density along the route to Port Everglades corresponds to mile markers 282 to 314 in Figure 40 (mile marker 314 is located at Hialeah Yard). The risk of transport along the Port Everglades Lead Track is bounded by the mainline track risk analysis with an average population density of 11,800 people/mile^2 at Mile Marker 308.

7 Weather and Terrain

The ambient air temperature and ground temperature of the Hialeah Yard, the Ports, the Bowden

Yard, and the routes were conservatively assumed to be the annual average temperature for the Jacksonville area, 68°F (20°C). This 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.[62]

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 suburbs and forests (1 m high). This selection was based on inspection of the test track environment during an Exponent inspection of the FECR track and via satellite imagery.

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[62] 49 CFR § 193.2059 – Flammable vapor-gas dispersion protection.

8 Results

Based on the forgoing discussion of the QRA assumptions, inputs, and calculations, the risk was calculated for a range of LNG ISO train consist configurations for each of the three routes and the rail yards and intermodal facilities. The risk results are presented in the form of Individual Risk contours, distance to Individual Risk thresholds, the Societal Risk integral, and Societal Risk as F-N curves for the fixed facilities and along the rail routes. For the proposed mainline routes, the risk results varied with demographics along the railroad. The underlying accident likelihoods and release scenarios are independent of the route demographics; thus, local population around the facilities and along the rail routes directly influences the calculated shipping risk. The risk was benchmarked against another flammable commodity, LPG, which has an established history of rail shipment. The LNG ISO risk results were then compared to quantitative risk criteria developed from those provided in NFPA 59A for stationary LNG plants.

The risk is first presented for a baseline case of a (b [redacted]-LNG ISO car consist shipped along the mainline at low speed, at high speed, and for movements in the rail yards and intermodal) facilities. This baseline case is then benchmarked against an equivalent energy content of LPG moved along the same routes and in the same rail yards to show that the risks of LNG shipping are comparable yet less than the risks of shipping LPG. Next, the effect of train configuration on the risk profiles for transporting and handling LNG is examined. Finally, the risk to sensitive targets is presented along Route 1 – Hialeah to Port of Miami and Route 2 – Hialeah to Port Everglades.

8.1 LNG ISO Shipping Baseline Risk

The LNG ISO shipping risk was first analyzed for the baseline train configuration since this configuration represents the highest risk. Configuring a train to contain (b) [redacted] LNG ISO cars in sequence will lead to a probability of multiple car derailment that maximizes the chances of up (4) to (b) [redacted] cars being involved in a LOC event. The probability of derailment is also highest when the LNG ISO cars are located near the front of the train. Thus, this configuration provides a (4) conservative baseline case for risk comparison.

Baseline Train Configuration:

Configuration 1 (C-1) [redacted] [redacted] ()Lb NG ISO car

positions: LNG ISO cars in sequenc (b)

e

(4)

The IR transects and 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 11,800 people per square mile. This population density will therefore correlate to the highest risk for train movement anywhere along the mainline. As a conservative approach, using this population density will bound the risk for all sections of mainline track.

8.1.1 Train Speeds Less Than 25 mph

A summary of the baseline risk metrics for the LNG mainline movement at train speeds less than 25 mph case is provided in Table 40. The SR integral is the area under the FN curve presented in Figure 43. For comparison, the SR integral for the upper risk criterion is

6.91×10^{-3} when integrated from 1 to 1,000 (or $4.61 \text{x} 10^{-3}$ when integrated from 1 to 100). The maximum IR is always less than the Zone 3 3×10^{-7} yr^{-1} threshold; thus, no sensitive targets will be affected in the applicable sections of the routes for any population density less than or equal to 11,800 people per square mile.

Table 40. Mainline train speeds less than 25 mph - summary of the risk metrics for LNG ISO car train movements.

Risk Metric	Mainline Train Speeds < 25 mph
	C-1 (Baseline)
SR Integral (total risk, yr^{-1})	3.63×10^{-4}
Maximum IR (yr^{-1})	2.70×10^{-7}
Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	N/A
Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	N/A
Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	N/A

The maximum Individual Risk value of 2.70×10^{-7} yr^{-1} is located on the route. A representative graph of the IR value versus distance from the PHAST Risk software is provided in Figure 42. The IR never reaches the Zone 3 threshold value of 3×10^{-7} yr^{-1} for train configuration C-1 for the highest population density at low speed.

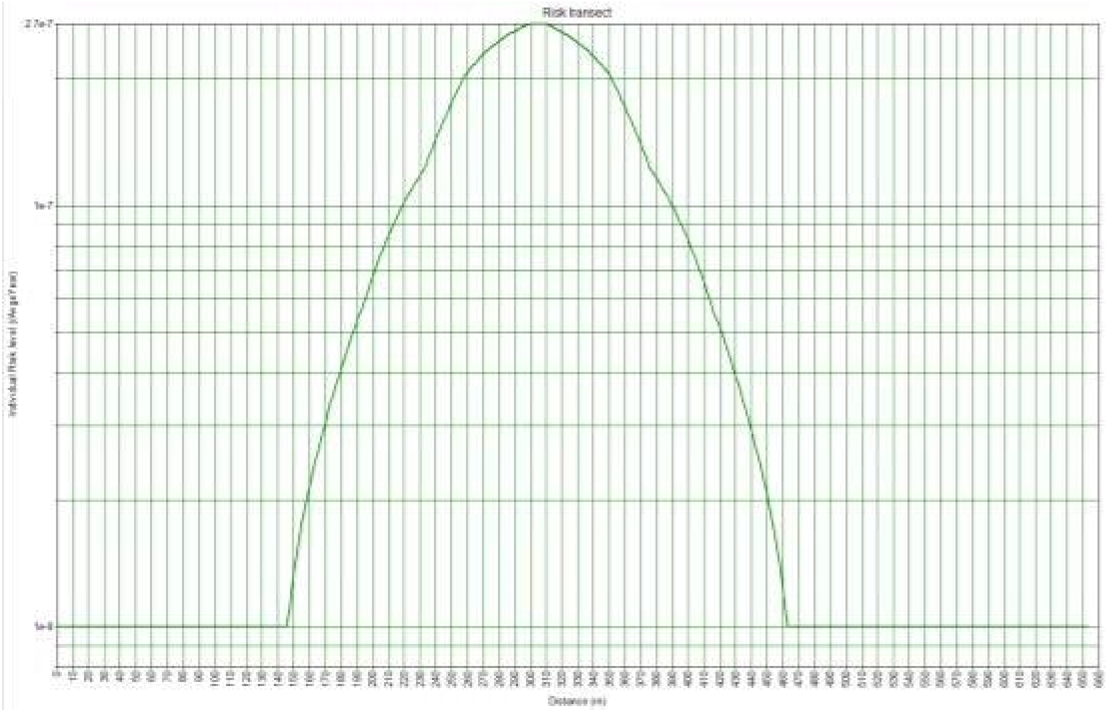

Figure 42. Representative graphical output of IR versus distance from PHAST Risk for slow train speed, train configuration C-1, and the highest population density of 11,800 people per square mile. The peak value is located at the route. The IR drops in a parabolic fashion moving perpendicularly away from the route.

The corresponding FN curve for the mainline track movement at train speeds less than 25 mph is provided in Figure 43 for train configuration C-1. The results indicate that the SR for the mainline movement at train speeds less than 25 mph falls within the “ALARP” region of acceptability.

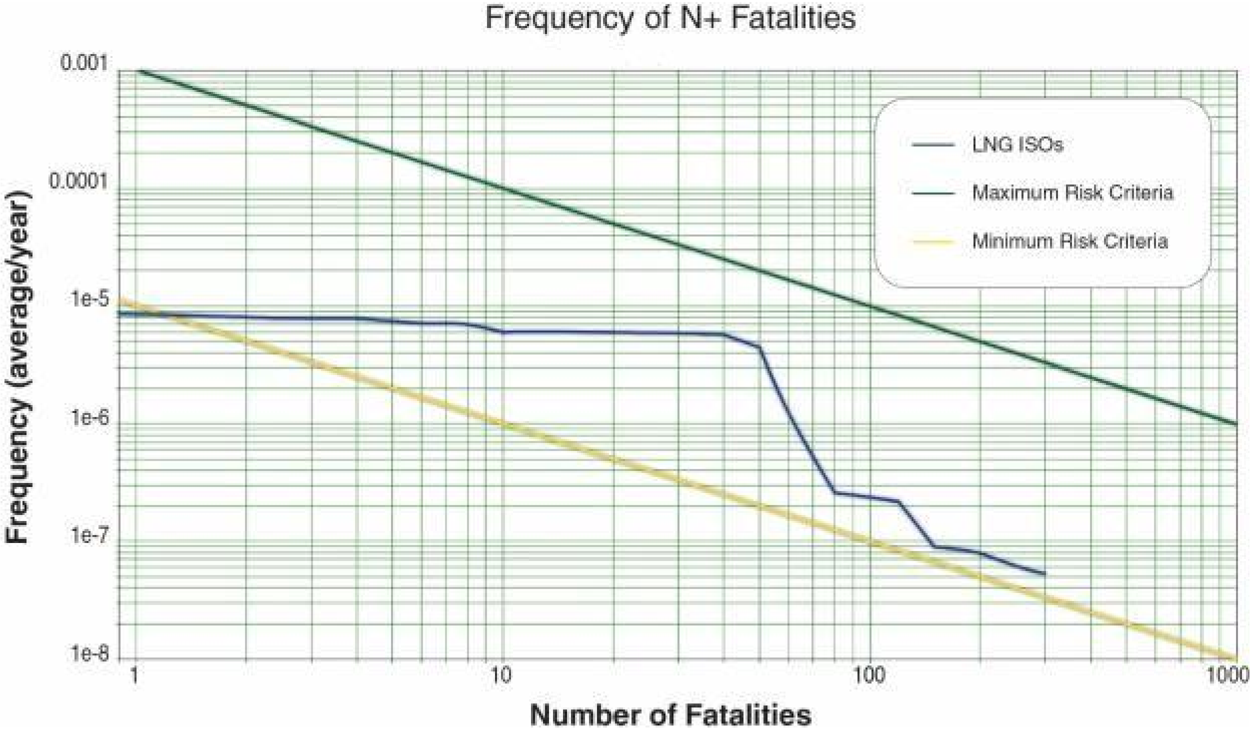

Figure 43. FN curve for the baseline train configuration C-1 mainline train movement for train speeds less than 25 mph along the highest population density portion of the mainline (at 11,800 people/mile^2).

8.1.2 Train Speeds between 25 mph and 60 mph

A summary of the baseline risk metrics for the LNG mainline movement at train speeds between 25 mph and 60 mph cases is provided in Table 41. The maximum IR (5.12×10^{-7} yr^{-1}) is less than the Zone 2 threshold criterion (1×10^{-6} yr^{-1}) for the highest population density (11,800 people per square mile); thus, IR for any lower population density will have a lower maximum IR. Sensitive targets falling within the Zone 3 (IR between 3×10^{-7} yr^{-1} and 1×10^{-6} yr^{-1}) range can be identified along the individual routes as necessary when accounting for the actual population density. The sensitive targets along the route are discussed in Section 8.4.

Table 41. Mainline train speeds between 25 mph and 60 mph - summary of the risk metrics for LNG ISO car train movements.

Risk Metric	Mainline Train Speeds 25 – 60 mph
	C-1 (Baseline)

SR Integral (total risk, yr^{-1})	7.14×10^{-4}
Maximum IR (yr^{-1})	5.12×10^{-7}
Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	N/A
Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	N/A
Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	200[55]

The maximum Individual Risk value is located on the route, and the IR drops moving away from the route. A representative graph of the IR value versus distance from the PHAST Risk software is provided in Figure 44. The maximum IR value of 5.12×10^{-7} yr^{-1} is located at the route, and the value drops in a parabolic fashion to the Zone 3 threshold value of 3×10^{-7} yr^{-1} by approximately 60 meters (200 feet) to either side of the route.

The corresponding FN curve for the mainline track movement at train speeds between 25 mph and 60 mph is provided in Figure 45 for C-1. The results indicate that the SR for the mainline movement at train speeds between 25 mph and 60 mph falls within the "ALARP" region.

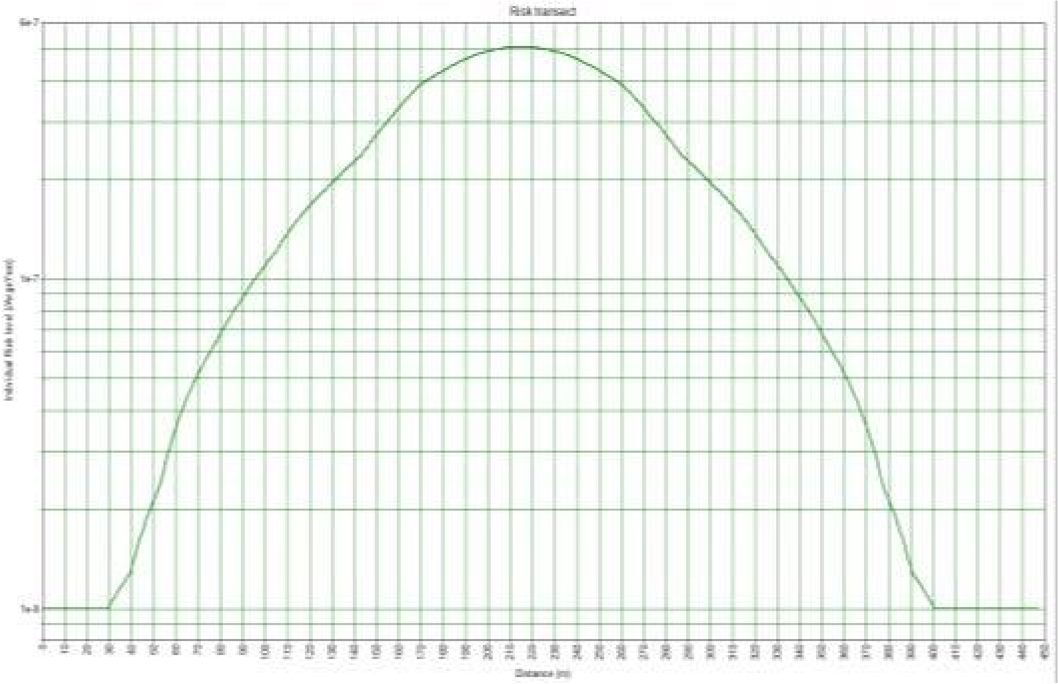

Figure 44. Representative graph of IR versus distance for high speed train, train configuration C-1, and a population density of 11,800 people per square mile. The peak value is located at the route. The IR drops in a parabolic fashion moving perpendicularly away from the route.

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[55] Note that the distance to the IR thresholds is reported as rounded to the nearest 5 feet increments.

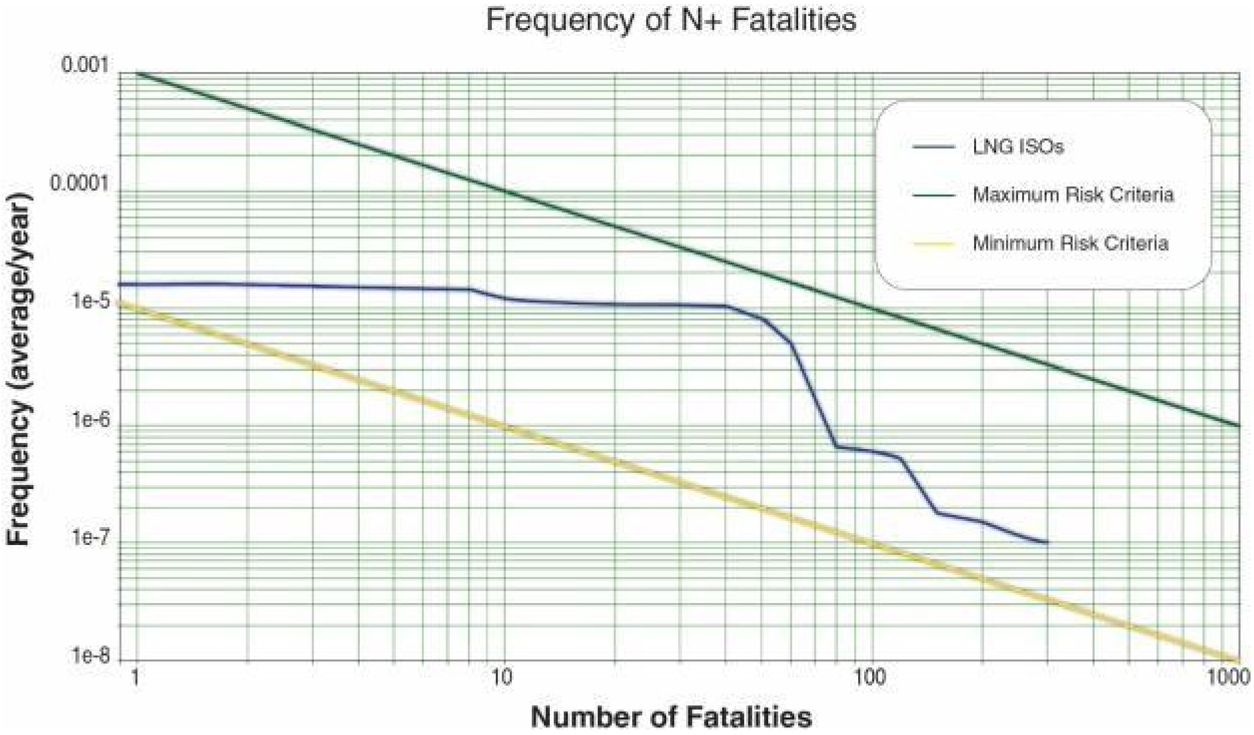

Figure 45. FN curve for the baseline train configuration C-1 mainline train movement for train speeds between 25 mph and 60 mph along the highest population density portion of the mainline (at 11,800 people/mile^2).

8.1.3 Rail Yards and Intermodal Facilities

The risk of LNG ISO handling and train movement within the rail yards and intermodal facilities was calculated for four scenarios: (1) Hialeah Yard, (2) Port of Miami, (3) Port Everglades, and (4) Bowden Yard. The risk represents the contribution from Lift On/Lift Off and train movement in the facilities for train configuration C-1.

Note that the locations of the lifting activities and the routes for train movements for each facility were applied as single points and fixed routes, respectively. In practice, lifting activities may occur along the tracks on the intermodal ramps at the facilities. By assuming that lifting only occurs at a single point, the total risk of the activity has been concentrated around this point. The actual risk for each facility posed by lifting will likely be less than represented by this conservative assumption since the risk would be distributed along each intermodal ramp's multiple tracks. Thus, this assumption conservatively bounds the anticipated risk for lifting activities at each facility.

The routes within each facility for LNG ISO train movements have been represented only along the main track to conservatively maximize the risk from train movements. In practice, the LNG ISOs are anticipated to move along many tracks within each yard; however, exact routes were unavailable for this analysis. By concentrating all accidents along the mainline, the distance to the risk thresholds is maximized. If all potential routes within the yard were modeled, then the distance to offsite risk levels would likely be reduced below the single main track route assumption.

The assumptions of using fixed points for lifting and fixed main track routes are anticipated to represent the maximum potential risk for each facility; therefore, these are the results provided below.

8.1.3.1 Hialeah Yard

The Hialeah Yard is the origin of LNG ISOs, and Lift On of the containers occurs there along the intermodal ramp. Two sets of assumptions were modeled for Hialeah in order to demonstrate the effects of route assumptions and the location of lifting on the risk outcomes. The first model (Route A) assumed that lifting occurred at a single point on the intermodal ramp and that train movement only occurred on the western-most yard track (see Figure 31). This simplified route was found to adequately represent the distance to the offsite Zone 3 IR threshold for train movement inside the facility regardless of the location of the track. By modeling lifting at a single point, the distance to the offsite IR thresholds was also conservatively calculated. The second model (Route B) calculated the risk for train movement along the western-most route, around the south loop track, and along the eastern-most track (see Figure 32). The movement along the easternmost track overlapped the intermodal ramp track, which was also used to represent lifting. The Route B model assumes that lifting activities could occur anywhere along the eastern intermodal ramp track. A further discussion of the model results is provided below, and serves as a basis for applying only the simplified route assumptions to the other facilities to represent the maximum potential distance to the offsite IR thresholds.

A summary of the baseline risk metrics for the LNG ISO car Hialeah Yard handling and movement cases is provided in Table 42. The maximum contributions to the IR and SR are from the Lift On activities. The SR Integral representing the total Societal Risk with the surrounding population (approximately 1,276 to 5,471 people per square mile) is approximately an order of magnitude larger than that for the mainline routes with assumed high population density as shown earlier in Table 40 and Table 41. The effects of localizing the lifting to a single point versus applying the activity along the intermodal ramp track are apparent in the table. The distance to each risk threshold is decreased when the lifting operation is distributed, and the Zone 1 - 1×10^{-5} yr^{-1} threshold onsite disappears when lifting is distributed. There is an insignificant difference between IR profiles for the train movement cases.

Table 42. Hialeah Yard - summary of the risk metrics for LNG ISO train movement and ISO lifting for two sets of route and lifting assumptions.

Risk Metric	Route A	Route B
	C-1 (Baseline)	**C-1 (Baseline)**
SR Integral (total risk, yr^{-1})	1.10×10^{-3}	1.51×10^{-3}
Maximum IR (yr^{-1})	6.39×10^{-5}	7.16×10^{-6}
Train Movement (from Track):		
Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	N/A	N/A

Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	N/A	N/A
Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	205[56]	205
ISO Lifting (from Point):		
Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	410	N/A
Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	515	455
Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	540	510

IR contour plots for Route A and Route B are overlaid on aerial images of the Hialeah Yard in Figure 46 and Figure 47 for train configuration C-1. The highest IR is observed onsite and is centered around the point of the Lift On activities assumed in the calculations. The Zone 3 boundary (IR isopleth of 3×10^{-7} yr^{-1}) is shown overlapping the nearby surrounding areas as represented by the yellow contours in the figures. Note that the layout of the Hialeah Yard, which is enclosed on the east side by an approximately 10 feet high wall, will also reduce the likelihood that flammable vapor clouds could expand beyond the property in that direction.[57] The offsite areas where IR is between 3×10^{-7} yr^{-1} and 1×10^{-6} yr^{-1} contain only commercial /industrial structures. The Zone 2 risk boundary crosses the property line at the north and south ends of the yard in an area of industrial activity, but the population densities in these areas are less than the Zone 2 threshold criterion of 7,250 to 23,300 persons per square mile. No Zone 3 sensitive targets were identified within regions of IR values greater than 3×10^{-7} yr^{-1} for either model. Given this analysis, the Individual Risk profiles for the Hialeah Yard are calculated to align with the fixed facility IR acceptability criteria stated in NFPA 59A (see Table 1).

The FN curves for the two routes, which represent the SR as the cumulative frequency versus severity, are provided in Figure 48 for train configuration C-1. The results indicate that the SR for the Hialeah Yard falls within the “ALARP” or tolerable region of acceptability according to the fixed facility SR criteria in NFPA 59A (see Figure 1).

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[56] Note that the distance to the IR thresholds is reported as rounded up to the nearest 5 feet increments.

[57] Note that the integral equation-based models in PHAST Risk are not suitable for modeling the barrier effects of walls on flammable vapor cloud dispersion; thus, the north-south track was used as the primary rail yard route.

Figure 46. The IR contours for the Hialeah Yard and baseline train configuration C-1 using Route A.

Figure 47. The IR contours for the Hialeah Yard and baseline train configuration C-1 using Route B.

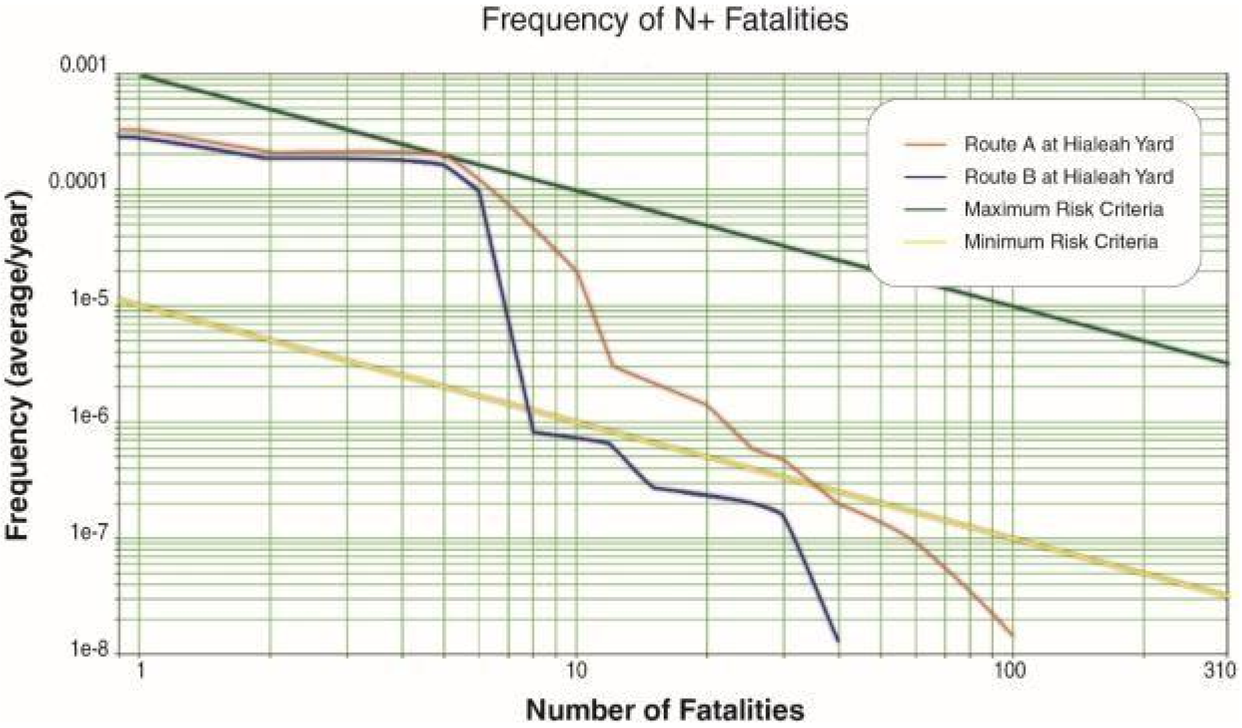

Figure 48. FN curve for Route A at the Hialeah Yard and baseline train configuration C-1.

8.1.3.2 Port of Miami Intermodal Facility

A summary of the baseline risk metrics for the LNG ISO car lifting and movement cases at the Port of Miami intermodal facility is provided in Table 43. The maximum contribution to the IR and SR is from the Lift Off activities. The SR Integral representing the total Societal Risk with the surrounding population is the same order of magnitude as the mainline route segments with high population. The surrounding population immediately around the intermodal facility was represented as 488 people per square mile whereas the cruise ship terminal had an assumed population of 19,000 people (with an equivalent density of 191,800 people per square mile).

Table 43. Port of Miami - summary of the risk metrics for LNG ISO train movement and ISO lifting.

Risk Metric	Port of Miami
	C-1 (Baseline)
SR Integral (total risk, yr^{-1})	1.69×10^{-4}
Maximum IR (yr^{-1})	4.45×10^{-5}
Train Movement (from Track):	
Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	N/A
Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	N/A

Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	175
ISO Lifting (from Point):	
Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	290
Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	525
Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	545

An IR contour plot for the Port of Miami intermodal facility is provided in Figure 49 for train configuration C-1. The frequency contours correspond to the summed individual risks for release scenarios occurring from the Lift Off operations and intermodal facility train movements. The highest IR is centered around the location of the Lift Off operations. This contour is maintained within industrial low population areas of the Port.

The areas outside the intermodal facility where IR is greater than 3×10^{-7} yr^{-1} contain only commercial/industrial structures, including a parking garage and shed to the north of the Lift Off operations. No Zone 3 sensitive targets were identified at IR values greater than 3×10^{-7} yr^{-1}. Given this analysis, the Individual Risk profiles for the Port of Miami intermodal facility are calculated to align with the fixed facility IR acceptability criteria stated in NFPA 59A (see Table 1).

Figure 49. The IR contours for the Port of Miami intermodal facility and baseline train configuration C-1. North is up.

The FN curve for the Port of Miami intermodal facility, which represents the SR as the cumulative frequency versus severity, is provided in Figure 50 for train configuration C-1. The results indicate that the SR for the Port of Miami intermodal facility falls within the “ALARP” or tolerable region of acceptability according to the fixed facility SR criteria in NFPA 59A (see Figure 1).

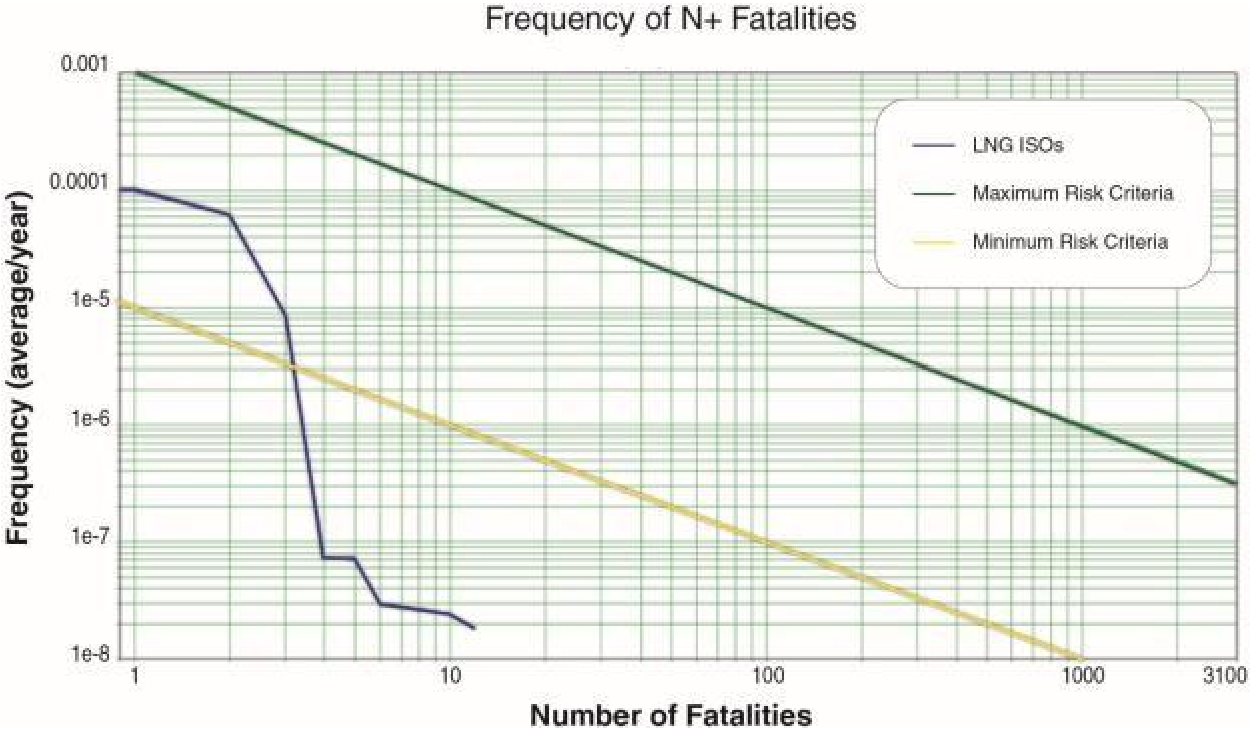

Figure 50. FN curve for the Port of Miami intermodal facility and baseline train configuration C-1.

8.1.3.3 Port Everglades Intermodal Facility

A summary of the baseline risk metrics for the LNG ISO car Port Everglades intermodal facility lifting and movement cases is provided in Table 44. The maximum contribution to the IR and SR is from the Lift Off activities. The SR Integral representing the total Societal Risk with the surrounding population (approximately 707 people per square mile) is the same order of magnitude as the mainline route segments with high population.

Table 44. Port Everglades - summary of the risk metrics for LNG ISO car movement and ISO lifting.

Risk Metric	Port Everglades
	C-1 (Baseline)
SR Integral (total risk, yr^{-1})	3.40×10^{-4}
Maximum IR (yr^{-1})	4.98×10^{-5}
Train Movement (from Track):	
Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	N/A

Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	N/A
Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	190
ISO Lifting (from Point):	
Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	330
Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	535
Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	550

An IR contour plot for the Port Everglades is provided in Figure 51 for train configuration C-1. The frequency contours correspond to the summed individual risks for release scenarios occurring from the Lift Off operations and intermodal facility train movements. The highest IR centers around the assumed location of the Lift Off operations.

On the northern boundary of the intermodal facility, the Zone 3 (3×10^{-7} yr^{-1}) frequency contour reaches Eller Drive; while on the other boundaries it overlaps only commercial/industrial structures and the undeveloped area. No Zone 3 sensitive targets were identified at IR values greater than 3×10^{-7} yr^{-1}. Given this analysis, the Individual Risk profiles for the Port Everglades intermodal facility are calculated to align with the fixed facility IR acceptability criteria stated in NFPA 59A (see Table 1).

Figure 51. The IR contours for Port Everglades intermodal facility and baseline train configuration C-1. North is up.

The FN curve for the Port Everglades intermodal facility, which represents the SR as cumulative frequency versus severity, is provided in Figure 52 for train configuration C-1. The results indicate that the SR for the Port Everglades intermodal facility falls within the “ALARP” or tolerable region of acceptability according to the fixed facility SR criteria in NFPA 59A (see Figure 1).

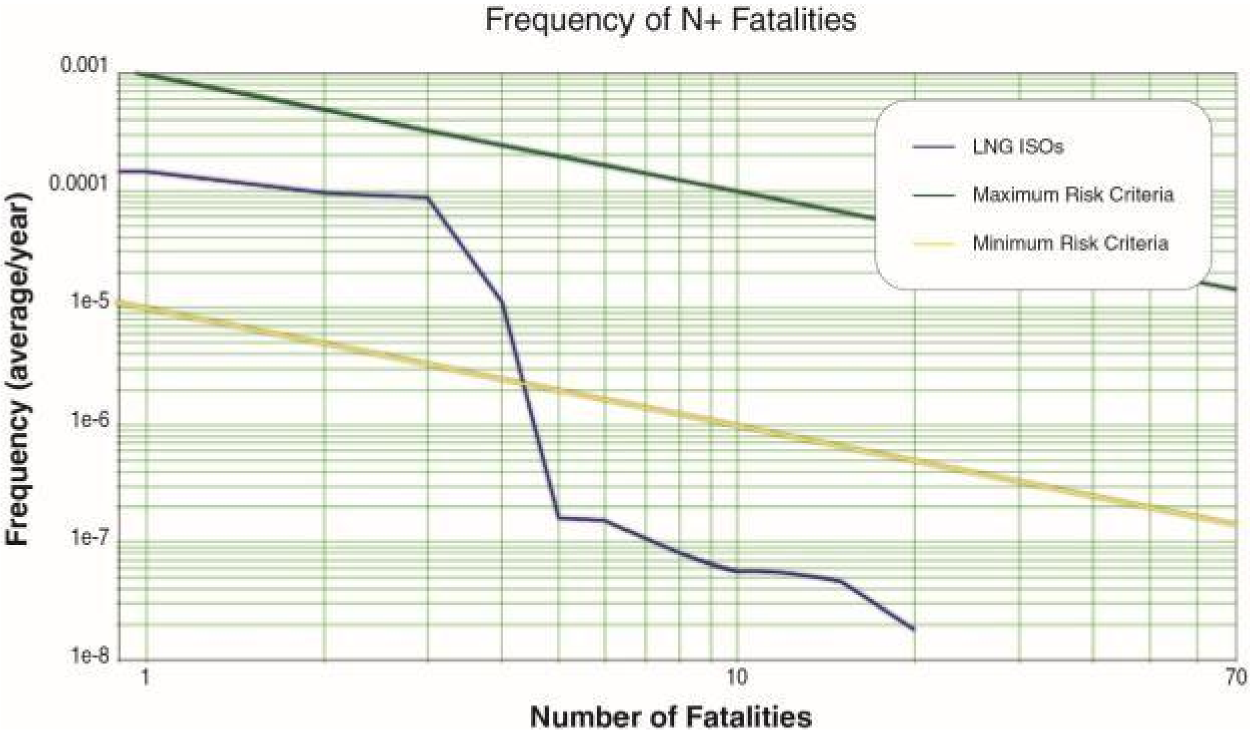

Figure 52. FN curve for the Port Everglades intermodal facility and baseline train configuration C-1.

8.1.3.4 Bowden Yard

A summary of the baseline risk metrics for the LNG ISO car Bowden Yard lifting and movement cases is provided in Table 45. The maximum contribution to the IR and SR is from the Lift Off activities. The SR Integral representing the total Societal Risk with the surrounding population (from approximately 478 to 5,720 people per square mile) is the same order of magnitude as the mainline route segments with high population.

Table 45. Bowden Yard - summary of the risk metrics for LNG ISO car movement and ISO lifting.

Risk Metric	Bowden Yard
	C-1
SR Integral (total risk, yr^{-1})	2.27×10^{-4}
Maximum IR (yr^{-1})	4.20×10^{-5}
Train Movement (from Track):	
Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	N/A
Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	N/A
Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	185
ISO Lifting (from Point):	

Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	290
Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	530
Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	560

An IR contour plot for the Bowden Yard is provided in Figure 53 for train configuration C-1. The frequency contours correspond to the summed individual risks for release scenarios occurring from the Lift Off operations and yard train movements. The highest IR is centered around the assumed point of Lift Off operations.

Moving away from the lifting operations, the IR decreases rapidly with distance. Zone 1 IR values higher than 1×10^{-5} yr^{-1} are maintained onsite, with the edge of the Zone 3 IR contour (3×10^{-7} yr^{-1}) traveling at most 100 feet from the FECR property line around the point of lifting. Areas offsite where IR falls within Zone 2 and Zone 3 (IR between 1×10^{-5} and 3×10^{-7} yr^{-1}) contain residential structures and commercial/industrial structures. The population density in this area is less than the Zone 2 threshold criterion of 7,250 to 23,300 persons/mile^2 for permitted populations. Given this analysis, the Individual Risk profiles for the Bowden Yard are calculated to align with the fixed facility IR acceptability criteria stated in NFPA 59A (see Table 1).

Figure 53. The cumulative IR contours for the Bowden Yard for baseline train configuration C-1. North is up.

The FN curve for the Bowden Yard, which represents the SR as the cumulative frequency versus severity, is provided in Figure 54 for train configuration C-1. The results indicate that the SR for Bowden Yard falls within the "ALARP" region of acceptability according to the fixed facility risk acceptability criteria in NFPA 59A (see Figure 1).

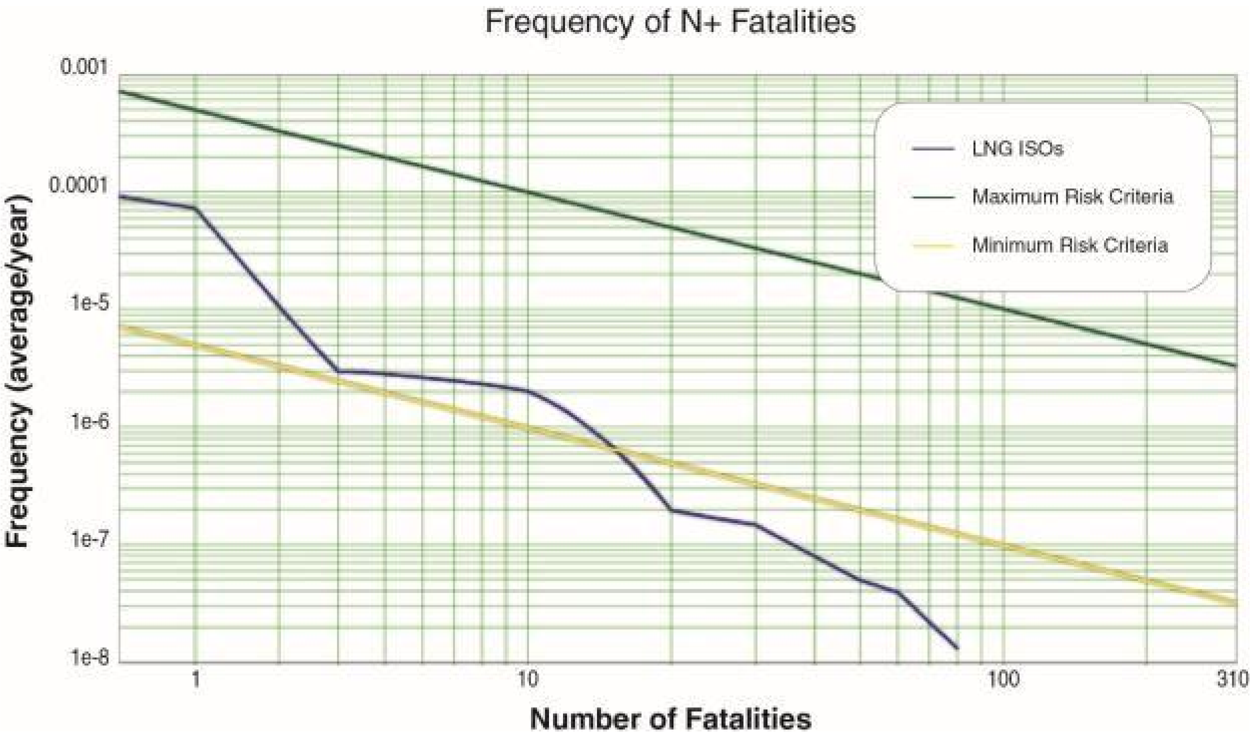

Figure 54. FN Curve for the Bowden Yard for baseline train configuration C-1.

8.2 Comparison with LPG Transportation

(b) (4)

The risks associated with handling and transporting LNG ISOs were benchmarked against the risks associated with transporting liquefied petroleum gas (also known as propane or LPG under the UN1075 designation) rail cars. LPG was chosen as a comparison flammable hazardous material due to its shipping history in the general rail industry and at FECR and because it is similar to LNG. LPG does not behave identically to LNG since LPG is a pressurized liquefied gas whereas LNG is a refrigerated liquefied gas, but it provides a useful HAZMAT commodity comparison. In 2015, . For the analysis here, the highest risk section of mainline transport (corresponding to a population density of 11,800 people/mile^2) and highest risk yard/intermodal facility (Hialeah Yard) were used to provide a consistent basis for comparison. The risk posed by an energy-equivalent quantity of LPG was analyzed for these cases.

(b)

The LPG rail cars were assumed to be transported in DOT-112 pressurized rail cars (nominal volume of 34,000 gallons); hence, the Lift On/Lift Off activities associated with LNG ISOs were not applicable to the LPG rail cars. To compare the LNG ISOs to LPG rail cars on an energy-equivalent basis, it was estimated that approximately 34,000 gallon LPG rail cars have the same energy content as [redacted] 10,000 gallon LNG ISOs.(4)[58] The accident rate methodologies developed in Section 3.1(4) were applied here to estimate the LPG car derailment rates and the LOC probabilities. The LPG event accident, derailment, and release event trees can be found in Appendix D.

8.2.1 LNG versus LPG Mainline Risks

[redacted]

The baseline train configuration C-1 was considered for the LNG ISOs along with a similar configuration for the LPG rail cars (cars blocked in a sequence starting at train position [redacted] A summary of the risk metrics for the LNG and LPG mainline movement cases is provided (4) (4) in Table 46. Overall, the analysis indicates that the risks for shipping an energy-equivalent quantity of LNG on the mainline are similar to those posed by LPG. The SR Integral for LPG is approximately twice the value of that for LNG for both low speed and high speed cases. There is no Zone 3 - 3×10^{-7} yr^{-1} IR contour for the LNG ISO mainline movement at train speeds less than 25 mph (whereas for LPG, a Zone 3 contour exists and the distance is 323-feet) and the distance to the 3×10^{-7} yr^{-1} IR contour is 612-feet for LPG compared to just 243-feet for LNG for train speeds between 25 mph and 60 mph.

Table 46. Comparison of risk metrics for LNG ISO car and LPG rail car mainline train movements.

Risk Metric	Speeds < 25 mph		Speeds Between 25 – 60 mph	
	LNG	LPG	LNG	LPG
SR Integral (total risk, yr^{-1})	3.63×10^{-4}	6.44×10^{-4}	7.14×10^{-4}	1.44×10^{-3}
Maximum IR (yr^{-1})	2.70×10^{-7}	3.95×10^{-7}	5.12×10^{-7}	8.85×10^{-7}
Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	N/A	N/A	N/A	N/A
Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	N/A	N/A	N/A	N/A
Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	N/A	323	200	623

The FN curves for the LNG ISO train configuration C-1 and LPG mainline movement, for train speeds less than 25 mph, along a one mile mainline track surrounded by a population of 11,800 people/mile^2 are provided in Figure 55. The complementary FN curves for train speeds between 25 mph to 60 mph, along a one mile mainline track surrounded by a population of 11,800 people/mile^2 are depicted in Figure 56. The FN curves for the LPG cases are similar to LNG, but both remain in the ALARP region.

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[58] The energy-equivalent amount of LPG relative to [redacted] 10,000 gallon LNG ISOs was estimated to be [redacted] gallons of LPG. Assumptions: density of LNG = 440 kg/m(4)^3, density of LPG = 500 kg/m^3, specific energy of LNG = 55.5 MJ/kg, and specific energy of LPG = 46.4 MJ/kg.

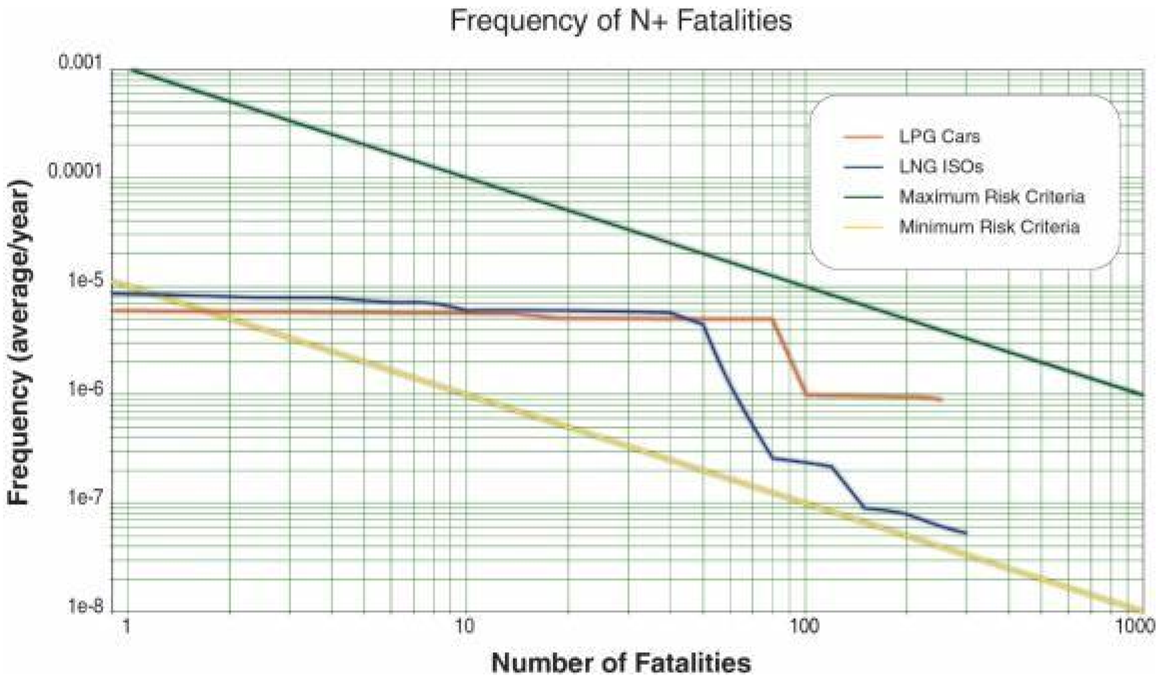

Figure 55. FN curve comparison for LNG ISOs and LPG rail car movement, for speeds less than 25 mph for the anticipated highest population density along FECR's rail.

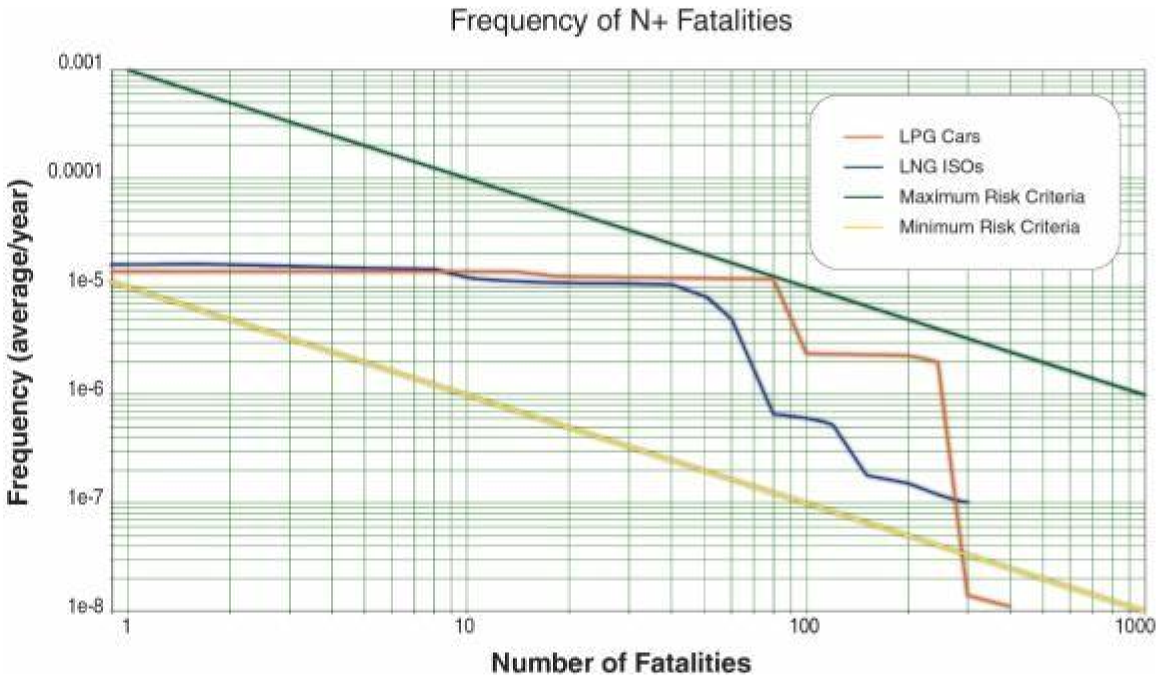

Figure 56. FN curve comparison for LNG ISOs and LPG rail car movement, for speeds between 25 mph and 60 mph for the anticipated highest population density along FECR's rail.

8.2.2 LNG versus LPG Yard/Intermodal Facility Risks

The baseline train configuration C-1 was considered for LNG ISOs along with a similar configuration for the LPG rail cars (three cars blocked in a sequence starting at train position 11). Only the Hialeah Yard was considered for this comparison, as this is the highest risk yard of the four considered (Bowden, Port of Miami, and Port Everglades being the other yards). A summary of the risk metrics for the LNG and LPG Hialeah Yard movement and handling cases are provided in Table 47. The SR Integrals are approximately the same order of magnitude for LNG and LPG.

Table 47. Comparison of risk metrics for LNG ISO car and LPG rail car movement and LNG ISO lifting in the Hialeah Yard. Note that there are no Lift On/Lift Off activities associated with the LPG cars.

Risk Metric	Hialeah Yard	
	LNG	LPG
SR Integral (total risk, yr^{-1})	1.10×10^{-3}	7.18×10^{-4}
Maximum IR (yr^{-1})	6.39×10^{-5}	4.74×10^{-6}
Maximum Distance to Zone 1 - 1×10^{-5} IR (ft)	410[59]	N/A
Maximum Distance to Zone 2 - 1×10^{-6} IR (ft)	515	560
Maximum Distance to Zone 3 - 3×10^{-7} IR (ft)	540	815

The IR contours for the LPG yard movements are overlaid on a satellite image of the Hialeah Yard with the corresponding contours for LNG ISO train configuration C-1 in Figure 57. Comparison of the Hialeah Yard IR contours for LPG and LNG indicates that the distances to the Zone 2 - 1×10^{-6} $yr^{-1}$and Zone 3 - 3×10^{-7} yr^{-1} contours are larger for LPG than for LNG (consistent with the findings from the mainline analysis) for train movement within the yard. The absence of a Zone 1 - 1×10^{-5} yr^{-1} contour for the LPG scenario is due to the lack of Lift On/ Lift Off activities and a corresponding risk component for LPG rail cars. Thus, the risks associated with yard movements and activities of LNG ISOs are similar to yard movement of LPG rail cars on an energy-equivalent basis.

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[59] The distance to these contours for LNG are associated with the lifting-related risk since that is the maximum contribution to the risk.

Figure 57. Comparison of IR contours for the movement of LNG ISOs and LPG in the Hialeah Yard.

The FN curve for the LPG Hialeah Yard movements is presented in Figure 58and compared against the FN curve for LNG ISO train handling and ISO lifting. The SR profiles of moving an energy-equivalent amount of LNG and LPG are similar, even in this instance where Lift On/Lift Off is included for the LNG ISOs but not applicable for LPG.

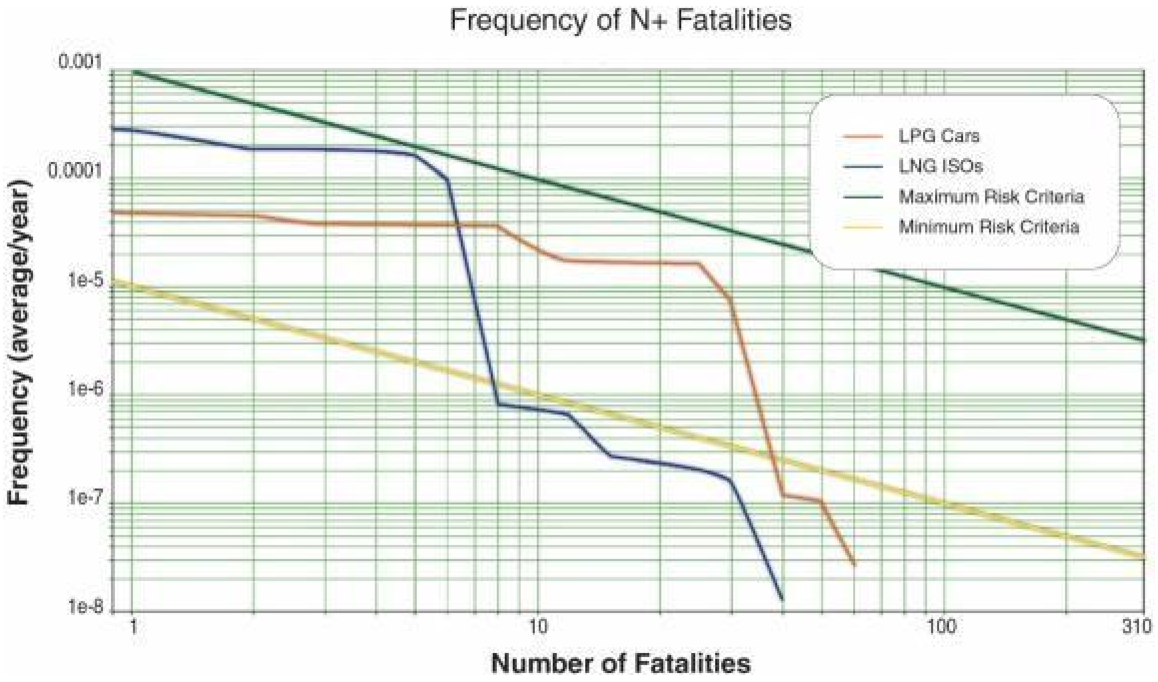

Figure 58. FN curve comparison for LNG ISOs and LPG train movements in the Hialeah Yard. Note that Lift On/Lift Off was not considered for LPG; the risk corresponds to only train movements in the yard.

8.3 Train Configuration and Risk Reduction for LNG ISO Transportation

The influence of train configuration on the calculated risk for transporting ten (10) LNG ISOs was calculated for the mainline train movement and rail yard and intermodal facility operations. Seven potential train configurations were considered in the analysis:

Train Configuration ID	Description
C-1	• (b) (4) [redacted]
C-2	• (b) (4) [redacted]
C-3	• (b) (4) [redacted]
C-4	• (b) (4) [redacted]
C-5	• (b) (4) [redacted]
C-6	• (b) (4) [redacted]
C-7	• (b) (4) [redacted]

8.3.1 Mainline LNG ISO Risk – Influence of Train Configuration

The different train configurations were evaluated for the mainline train movement scenarios at

(1) train speeds less than 25 mph and (2) train speeds between 25 mph and 60 mph. The SR and IR were calculated as a function of population density for a one mile long section of track with a surrounding population density of 11,800 people/mile^2. This mile segment is the highest population density mile track along the entire main line route and will, therefore, bound the highest risk for train movement along the entire mainline.

8.3.1.1 Train Speeds Less Than 25 mph

From the seven train configurations, it was found that there was little change in the risk from configurations C-4 to C-7 for the mainline train movement scenarios at train speeds less than 25 mph. Thus, the first four train configurations (C-1 through C-4) are discussed here. A summary of the risk metrics for the LNG mainline movement at train speeds less than 25 mph cases is provided in Table 48. The baseline train configuration C-1 bounds the highest risk and is used as the basis for comparison purposes. The reduction in the SR Integral for each configuration is compared against C-1 in the table. The maximum IR is always less than the Zone 3 - 3×10^{-7} yr^{-1} threshold for these train configurations. Based on comparison of the SR Integral for the four configurations, a risk reduction of 38.8% may be realized by using C-4 instead of C-1 for the mainline movement at train speeds between 25 mph and 60 mph.

Table 48. Summary of the risk metrics for slow speed LNG ISO car train movements.

Risk Metric	**Mainline Train Speeds < 25 mph**			
	C-1	C-2	C-3	C-4
SR Integral (total risk, yr^{-1})	3.63×10^{-4}	2.60×10^{-4}	2.40×10^{-4}	2.22×10^{-4}
Maximum IR	2.70×10^{-7}	1.93×10^{-7}	1.79×10^{-7}	1.66×10^{-7}
Distance to 3×10^{-7} yr^{-1}IR (ft)	N/A	N/A	N/A	N/A
Risk Reduction	--	28.4%	33.9%	38.8%

The FN curves for these four train configurations are depicted in Figure 59. The results indicate that the SR for the mainline movement at train speeds less than 25 mph falls within the “ALARP” or tolerable region of acceptability, regardless of train configuration.

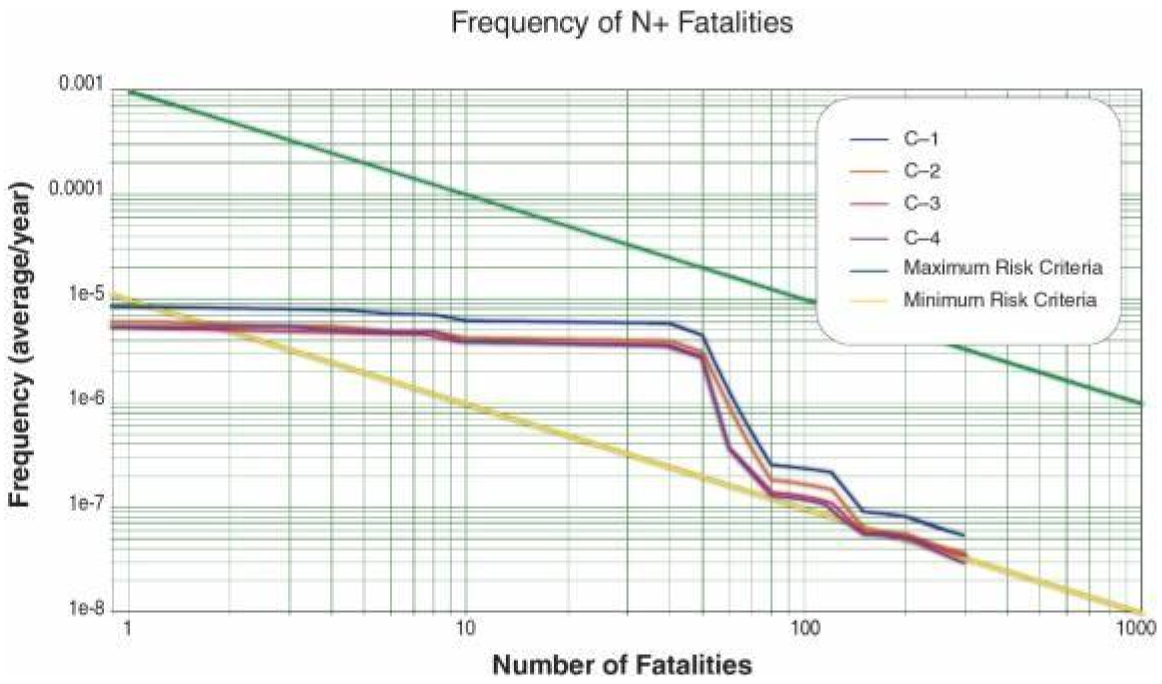

Figure 59. Comparison of FN curves for mainline train speeds less than 25 mph for four train configurations.

8.3.1.2 Train Speeds Between 25 mph and 60 mph

All seven train configurations were evaluated for the mainline train movement scenarios for train speeds from 25 mph to 60 mph, inclusive. A summary of the risk metrics for the LNG mainline movement at train speeds from 25 mph to 60 mph cases is provided in Table 49. The baseline train configuration C-1 bounds the highest risk and is used for comparison purposes. The reduction in the SR Integral for each configuration is compared against C-1. The maximum IR observed is always less than Zone 2 - 1×10^{-6} yr^{-1} for all configurations, and it is less than the Zone 3 - 3×10^{-7} yr^{-1} threshold for train configurations C-6 and C-7. Based on comparison of the SR Integral for the seven configurations, a risk reduction of 38.0% may be realized by using C-4 instead of C-1 for the mainline movement at train speeds between 25 mph and 60 mph. Further, a risk reduction of 49.0% may be realized by using C-7 instead of C-1.

Table 49. Summary of the risk metrics for high speed LNG ISO car train movements.

Risk Metric	Mainline Train Speeds ≥25 to ≤60 mph						
	C-1	C-2	C-3	C-4	C-5	C-6	C-7
SR Integral (total risk)	7.14×10^{-4}	4.92×10^{-4}	4.63×10^{-4}	4.43×10^{-4}	4.14×10^{-4}	3.75×10^{-4}	3.64×10^{-4}
Maximum IR	5.12×10^{-7}	3.54×10^{-7}	3.42×10^{-7}	3.29×10^{-7}	3.14×10^{-7}	2.76×10^{-7}	2.68×10^{-7}

Distance to 3×10^{-7} IR (ft)	200	120	110	80	60	N/A	N/A
Risk Reduction	--	31.1%	35.2%	38.0%	42.0%	47.5%	49.0%

The FN curves for the seven train configurations are compared in Figure 60. The results indicate that the SR for the mainline movement at train speeds between 25 mph and 60 mph falls within the “ALARP” or tolerable region, regardless of train configuration.

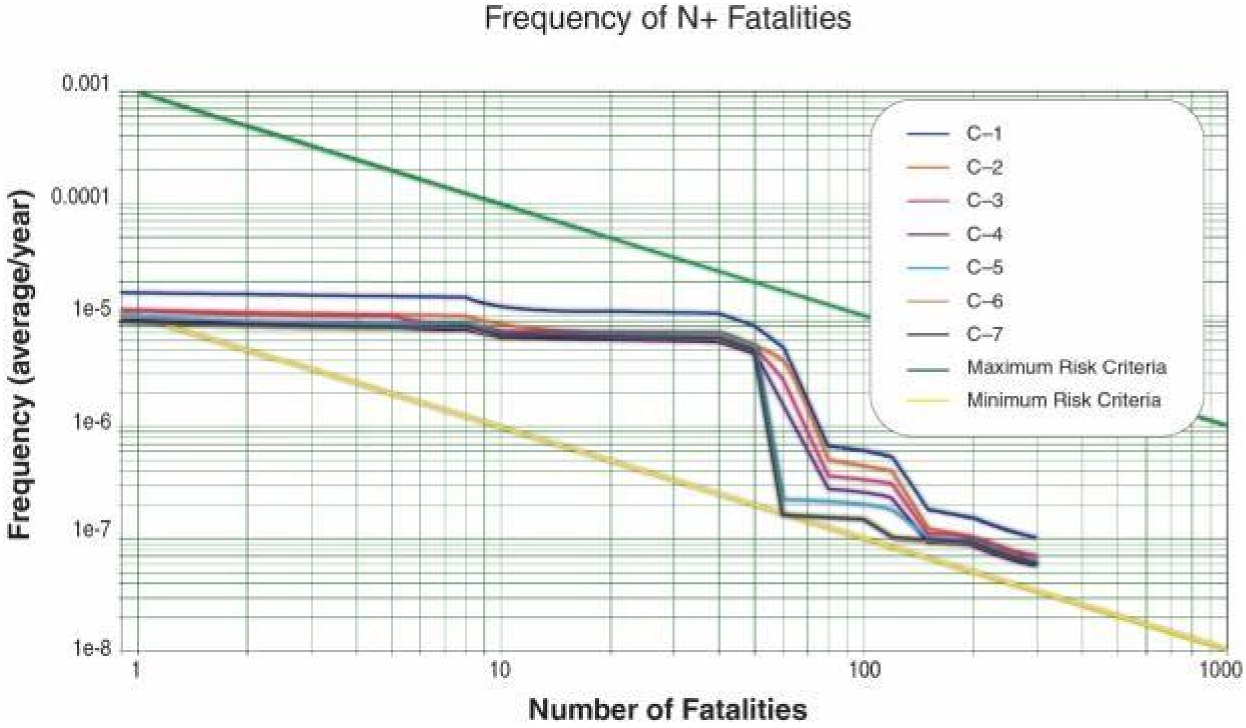

Figure 60. Comparison of FN curves for mainline train speeds between 25 mph and 60 mph for seven train configurations.

8.3.2 Rail Yards and Intermodal Facilities LNG ISO Transportation – Influence of Train Configuration

The different train configurations were evaluated for LNG ISO movement and handling within the rail yards and intermodal facilities: (1) Hialeah Yard, (2) Port of Miami, (3) Port Everglades, and (4) Bowden Yard.

8.3.2.1 Hialeah Yard

The first four train configurations (C-1 through C-4) are discussed for the train movement and lifting of LNG ISOs in the Hialeah Yard.[68] A summary of the risk metrics for the LNG ISO car Hialeah Yard handling and movement cases is provided in Table 50. The risk reduction presents the percent reduction in the SR Integral based on the C-1 (baseline) train configuration case. The maximum IR observed is the same for all cases, as it is driven by the Lift On activities which are not influenced by the train configuration. Based on comparison of the SR Integral for the four configurations, a risk reduction of 7.27% may be realized by using C-4 instead of C-1 for the Hialeah Yard movement and handling operations. The risk results for C-1, which are the basis for comparison, are discussed above in Section 8.1.3.

Table 50. Hialeah Yard - summary of the risk metrics for LNG ISO car movements and LNG ISO lifting for multiple train configurations.

Risk Metric	Hialeah Yard			
	C-1	C-2	C-3	C-4
SR Integral (total risk)	1.10×10^{-3}	1.04×10^{-3}	1.03×10^{-3}	1.02×10^{-3}
Maximum IR	6.39×10^{-5}	6.39×10^{-5}	6.39×10^{-5}	6.39×10^{-5}
Risk Reduction	--	5.45%	6.36%	7.27%

The Zone 3 isopleth of 3×10^{-7} yr^{-1} travels at most 200 feet from the train route for C-1. The distance to this isopleth did not vary significantly compared to the other three train configurations. The primary difference was represented in the shape of the 1×10^{-6} yr^{-1} contour at the north end of the facility. This contour's area decreased with each successive train configuration from C-2 to C-4. The offsite areas where IR is greater than 3×10^{-7} yr^{-1} contain only commercial/industrial structures. The population densities in these areas are less than the Zone 2 threshold criterion of 7,250 to 23,300 persons/mile^2 for permitted populations. No Zone 3 sensitive targets were identified within the contours having IR values greater than 3×10^{-7} yr^{-1}. The maximum IR observed at the Hialeah Yard was centered around the assumed point of Lift On activities for all cases. Given this analysis, the IR for the Hialeah Yard aligns with the fixed facility IR acceptability criteria stated in NFPA 59A (see Table 1) for all train configurations C1 to C-4.

The comparison of FN curves for the facility shows that the risk profile drops similar to that

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[68]

presented in Figure 59 for the mainline; however, the decrease in risk from C-1 to C-4 is only slight since the lifting activities dominate. The results indicate that the SR for the Hialeah Yard falls within the “ALARP” or tolerable region of acceptability according to the fixed facility SR criteria in NFPA 59A (see Figure 1), regardless of train configuration.

8.3.2.2 Port of Miami Intermodal Facility

Based on the results for Hialeah, train configurations C-1 and C-4 are reported for the movement and handling of LNG ISOs in the Port of Miami intermodal facility.[69] A summary of the risk metrics for the LNG ISO car Port of Miami lifting and movement cases is provided in Table 51. The risk reduction presents the percent reduction in the SR Integral based on the C-1 (baseline) train configuration case. Based on comparison of the SR Integral for the two configurations, a risk reduction of 4.14% may be realized by using C-4 instead of C-1 for the Port of Miami intermodal operations. The maximum IR observed and the FN curve are virtually unchanged for C-4, as the risk is driven by the Lift Off activities which are not influenced by the train configuration. The risk results for C-1 are discussed above in Section 8.1.3. Given this analysis, the IR and the SR for the Port of Miami intermodal facility align with the fixed facility IR and SR acceptability criteria stated in NFPA 59A (see Table 1 and Figure 1) for both train configurations C-1 and C-4. Since train configuration C-1 represents the most significant risk of all configurations considered, it is anticipated that the other train configurations will have similar or less risk.

Table 51. Port of Miami - summary of the risk metrics for LNG ISO car movement and lifting for multiple train configurations.

Risk Metric	Port of Miami	
	C-1	C-4
SR Integral (total risk)	1.69×10^{-4}	1.62×10^{-4}
Maximum IR	4.45×10^{-5}	4.41×10^{-5}
Risk Reduction	--	4.14%

8.3.2.3 Port Everglades Intermodal Facility

Based on the results for Hialeah, train configurations C-1 and C-4 are reported for the movement and handling of LNG ISOs in the Port Everglades intermodal facility.[60] A summary of the risk metrics for the LNG ISO car Port Everglades lifting and movement cases is provided in Table 52. The risk reduction presents the percent reduction in the SR Integral based on the C1 (baseline) train configuration case. Based on comparison of the SR Integral for the two configurations, a risk reduction of 5.00% may be realized by using C-4 instead of C-1 for the Port Everglades intermodal operations. The risk results for C-1 are discussed above in Section 8.1.3. Given this analysis, the IR and the SR for the Port Everglades intermodal facility align with the fixed facility IR and SR acceptability criteria stated in NFPA 59A (see Table 1 and Figure 1) for both train configurations C-1 and C-4. Since train configuration C-1 represents

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[69]

[60] The IR contours are overlaid on an aerial image of the facility for these four train configurations in Appendix F, and the FN curves for the four train configurations can be found in Appendix G.

the most significant risk of all configurations considered, it is anticipated that the other train configurations will have similar or less risk.

Table 52. Port Everglades - summary of the risk metrics for LNG ISO car movement and lifting for multiple train configurations.

Risk Metric	Port Everglades	
	C-1	C-4
SR Integral (total risk)	3.40×10^{-4}	3.23×10^{-4}
Maximum IR	4.98×10^{-5}	4.95×10^{-5}
Risk Reduction	--	5.00%

8.3.2.4 Train Configuration Risk Comparison – Bowden Yard

Based on the results for Hialeah, train configurations C-1 and C-4 are reported for the movement and lifting of LNG ISOs in the Bowden Yard.[71] A summary of the risk metrics for the LNG ISO car Bowden Yard lifting and movement cases is provided in Table 53. The risk reduction presents the percent reduction in the SR Integral based on the C-1 (baseline) train configuration case. The maximum IR observed is virtually unchanged for both cases, as it is driven by the Lift Off activities which are not influenced by the train configuration. Based on comparison of the SR Integral for the two configurations, a risk reduction of 14.1% may be realized by using C-4 instead of C-1 for the Bowden Yard movement and handling operations.

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[71]

The risk results for C-1 are discussed above in Section 8.1.3. Given this analysis, the IR and the SR for the Bowden Yard align with the fixed facility IR and SR acceptability criteria stated in NFPA 59A (see Table 1 and Figure 1) for both train configurations C-1 and C-4. Since train configuration C-1 represents the most significant risk of all configurations considered, it is anticipated that the other train configurations will have similar or less risk.

Table 53. Bowden Yard - summary of the risk metrics for LNG ISO car movement and lifting for multiple train configurations.

Risk Metric	Bowden Yard	
	C-1	C-4
SR Integral (total risk)	2.27×10^{-4}	1.95×10^{-4}
Maximum IR	4.20×10^{-5}	4.17×10^{-5}
Risk Reduction	--	14.1%

8.4 Sensitive Target Analysis

The FRA requested that FECR perform an analysis of potentially sensitive establishments along the proposed railway routes. There is no current regulatory quantitative risk criteria for Individual Risk or Societal Risk of LNG transportation by rail, and the criteria used here were developed from those applicable to stationary LNG plants. For stationary LNG plants, NFPA 59A does not permit sensitive establishments, such as churches, schools, hospitals, and major public assembly areas, to be located within an Individual Risk (IR) greater than 3×10^{-7} per year.[61] There are many differences in the hazards and risk profile between a stationary facility and a transportation activity. Acceptable quantitative risk criteria for transportation of hazardous materials typically represent higher risk levels than stationary facilities. However, the Zone 3 risk from NFPA 59A was used as the benchmark for evaluation of risk to offsite populations.

The full list of potentially sensitive establishments and satellite maps depicting the Zone 3 (3×10^{-7} yr^{-1}) IR contours along the routes are provided in Appendix G. In the appendix, Tables G-1 and G-2 list potentially sensitive establishments along Routes 1 and 2, respectively. The satellite maps are provided as collages for each route and individual maps covering approximately one-mile sections of the routes.

Google Earth Pro was used to identify potentially sensitive establishments near the proposed railway routes. In this analysis, the following categories of establishments were considered to be potentially sensitive:

- Schools, grades elementary and above
- Churches, synagogues, mosques, and other houses of worship
- Senior care facilities
- Hospitals
- Sports arenas

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[61] Chapter 15.10.1 of NFPA 59A (2016) *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*.

By using Google Earth Pro’s built-in layers database that categorizes different types of establishments (“Banks/ATMS”, “Pharmacy”, etc.) and by validating their location and existence through internet searches, a list of potentially sensitive establishments was developed for the routes. Establishments where the nearest edge of the building was less than approximately (b) [redacted] feet from the centerline of the railroad track were included in the analysis. The establishments and the approximate distance to the railway are listed in the following (4) tables. The establishments are then identified on aerial maps of the routes with the maximum distance to the Zone 3 (3×10^{-3} yr^{-1}) Individual Risk contour overlaid along the route.

(b) (4) [redacted]

The maximum distance to the contour along the routes is (b) [redacted] feet assuming the train is traveling at high speed (from 25 and 60 mph) for train configuration C-1 (i.e., (4) (b) [redacted] LNG ISOs in sequence from train position). For any sections of the routes where the speed is maintained (4) at less than or equal to 25 mph, there will be no Zone 3 Individual Risk contour. Note that the last one-mile section of Route 1 before the drawbridge to the Port of Miami has a maximum speed of 25 mph; thus, no Zone 3 risk contour is present on the figures. For the fixed railyard facilities, the distance to the contour is shown based on the fixed facility analyses for the Hialeah Yard, Port of Miami intermodal facility, and the Port Everglades intermodal facility. The contours as shown in the figures are representative of the distance to the contour, and the actual calculated distance should be relied upon in all cases. An example of the last two onemile maps for Route 1, including downtown Miami and the Port of Miami, are provided in Figure 61. The maps illustrate a section of the route where the speed restriction to 25 mph eliminates the potential Zone 3 IR contour.

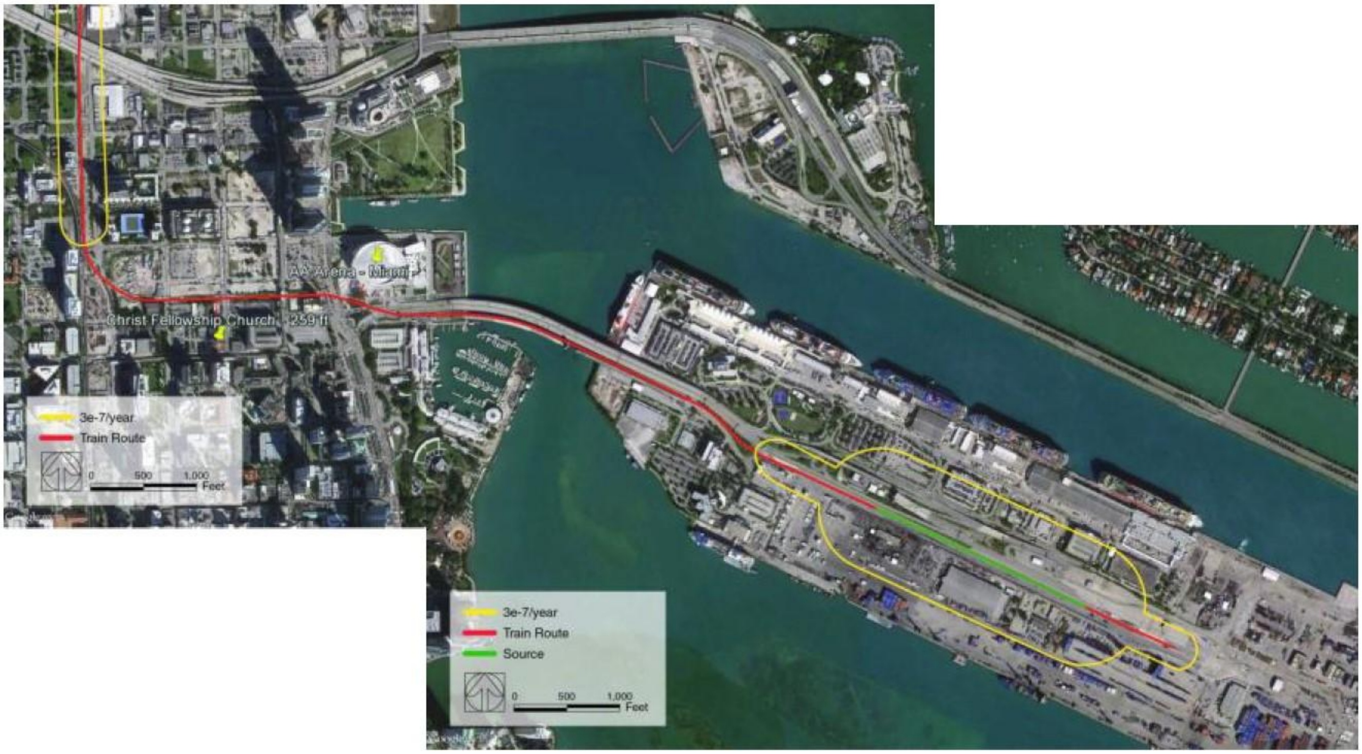

Figure 61. Composite aerial maps with Zone 3 contour depicted for Route 1 for the last two maps including the Port of Miami.

9 Limitations

As requested by Florida East Coast Railway, LLC, Exponent conducted a Quantitative Risk (b) (4) Assessment (QRA) study addressing FECR movement of LNG ISO containers 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 References

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3. Appendix B: Survey of Worldwide Risk Criteria Applications, *Guidelines for Developing Quantitative Safety Risk Criteria*. Center for Chemical Process Safety, AIChE (2009).
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7. Exponent report titled: "HAZID Study Report, Florida East Coast Railway Dual-Fuel Locomotive LNG Tender Project," issued June 23, 2014.
8. Exponent report titled: "HAZID Study Report, Florida East Coast Railway Dual-Fuel Locomotive LNG Tender Project, Updated to Reflect Chart LNG Tender" issued January 2, 2015.
9. Exponent report titled: "Integration HAZID Study Report, Florida East Coast Railway Dual-Fuel Locomotive and LNG Tender Project," issued December 12, 2014.
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Appendix B FECR "Movement of LNG Containers" Document, 10/8/2015

Appendix C FECR “LNG ISO Container Proposed Routes” Document, 10/6/2015

Appendix D LNG ISO and LPG Rail Car

Derailment and Loss of Containment Event Trees Appendix E

~~FECR Mainline Map~~ with Population Densities Appendix F

~~Societal Risk (SR) FN Curves~~ Appendix G Potentially Sensitive Targets

Results for Zone 3 Individual Risk