MARY KAY O'CONNOR PROCESS SAFETY CENTER
TEXAS A&M ENGINEERING EXPERIMENT STATION

21st Annual International Symposium
October 23-25, 2018 | College Station, Texas

Quantitative Risk Calculations for a U.S. DOT Natural Gas Pipeline Using Population Classifications

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Keywords: QRA, natural gas pipeline, risk analysis

Abstract

Over the past several years, Quest Consultants Inc. has conducted quantitative risk analysis (QRA) and risk assessment studies for a range of pipelines in the United States and abroad. In most instances, the risk acceptance or tolerability criteria are defined by the individual risk (IR) to a person; often this risk is presented as location specific individual risk (LSIR). The LSIR is a measure of the risk to a person who is continuously at a specific location.

In recent years, there has been increasing dependence on the use of societal risk acceptance or tolerability criteria, including the risk associated with pipelines. Pipelines are often described as linear sources of risk, like highways and rail lines. The risk analysis methodology used to calculate the risk associated with fixed facilities (e.g., refineries and chemical plants) cannot be directly applied to linear risk sources.

This paper presents a risk calculation methodology that can be applied to linear risk sources, like natural gas pipelines, and compares the societal risk indices for U.S. DOT pipeline classes.

INTRODUCTION

Natural gas pipelines that service public populations fall into three main groups: transmission, distribution, and home service. In general, these three pipelines are defined by the pressure of the natural gas transported in the pipeline. From the guidance provided by the United State Department of Transportation (USDOT) the pressures in these three pipeline classes can be defined as follows.

- Transmission pipelines operate at pressures above 500 psig (pounds per square inch gauge)
- Distribution pipelines operate between 200 psig and 10 psig
- Home service lines operate at pressures below 10 psig

There is a current interest in describing the risk associated with the transport of natural gas by pipeline as part of the evaluation of its potential impacts. The natural gas that is to be transported in the pipelines does not have significant amounts of toxic components. Thus, the primary hazards that have the potential to extend more than a few feet from these pipelines are:

- Jet fire radiant hazard
- Flash fire radiant hazard
- Vapor cloud explosion overpressure hazard

For natural gas pipelines, the flash fire hazard zone is often smaller than the jet fire hazard zone. In addition, the potential to develop significant overpressure (high enough to injure or kill members of the public) requires a degree of congestion and/or confinement that might not exist along portions of the pipeline route or even an entire pipeline. Thus, the jet fire is the dominant hazard along the pipeline route. Any release of natural gas from a pipeline, once ignited, will form a momentum-based jet fire. The radiant impact from the jet fire will dominate the risk along the pipeline route.

The USDOT collects data on natural gas pipeline failures that result in one or more fatalities (public and worker combined). The data collected by the USDOT produce backward-looking statistics and do not provide an accurate view of what could happen in the future since *where* a release occurs along a pipeline route can have a significant impact on the number of fatalities and injuries. Quantitative Risk Analysis (QRA) studies are forward-looking studies that are designed to show potential future impacts. Since the designer of the QRA cannot determine exactly where a release might occur along a pipeline route, the designer of the QRA must use a pipeline failure rate (number of pipeline failures per year per length [e.g., mile]) in a predictive mode. In this manner, a release along the pipeline route may be thought of as the same anywhere along the route. The failure rate can be modified by the inclusion of ancillary pipeline equipment such as regulator stations, etc.

POPULATION

The most difficult and site-specific aspect of calculating the risk associated with natural gas pipelines has to do with the population distribution along the pipeline route. Unlike fixed facilities such as a refinery where the population around the facility fence line is assumed to be constant and has to be evaluated and used as an input to the overall risk analysis, the population along a pipeline route can vary along the route. Thus, while the potential for a release and the sizes of the hazard zones might not change significantly along the pipeline route, the risk to the public might vary due to the variation in population (density and/or distance from the pipeline).

The USDOT uses the density of buildings in order to define the pipeline class location[1]. The USDOT class location is dependent on the density of buildings along a one-mile segment of the pipeline out to 220 yards perpendicular the pipeline. This area is equivalent to one-quarter of a square mile (1.0 mile * 440 yards [1/4 of a square mile]). The USDOT provides the following definitions for the pipeline classes.

USDOT Class	Definition
Class 1	Fewer than 10 buildings in the one-quarter square mile area.
Class 2	From 10 to 46 buildings in the one-quarter square mile area.
Class 3	More than 46 buildings in the one-quarter square mile area or if the pipeline lies with 100 yards (90 meters) of a building or area that is occupied by 20 or more persons at least 5 days a week for 10 weeks in any 12-month period. (e.g., playground, golf course, etc.)
Class 4	Any Class (1, 2, or 3) where buildings with four or more stories are prevalent.

Natural Gas Transmission Pipeline Failure Data

The USDOT onshore natural gas transmission pipeline data by class from 2010 to 2016 is listed in Table 1. As would be expected, Class 1 which occurs primarily in rural areas, dominates the total mileage. However, as both Table 1 and Figure 1 show, the failure rate for the natural gas transmission pipeline is fairly constant for the different USDOT pipeline class definitions. When viewing Table 1 and Figure 1, it should be noted that the total amount of onshore Class 4 natural gas transmission pipelines in service is less than 0.4 % of the total mileage.

Table 1. Accidental Release Rate for Onshore Natural Gas Pipelines by Class

Transmission Mileage by Class	Failures	Onshore [miles]	Accidental Release Rate [per mile per year]
Class 1	228	1,633,139	1.396E-04
Class 2	21	212,017	9.905E-05
Class 3	40	235,646	1.697E-04
Class4	1	7,432	1.346E-04
Total	290	2,088,234	1.389E-04

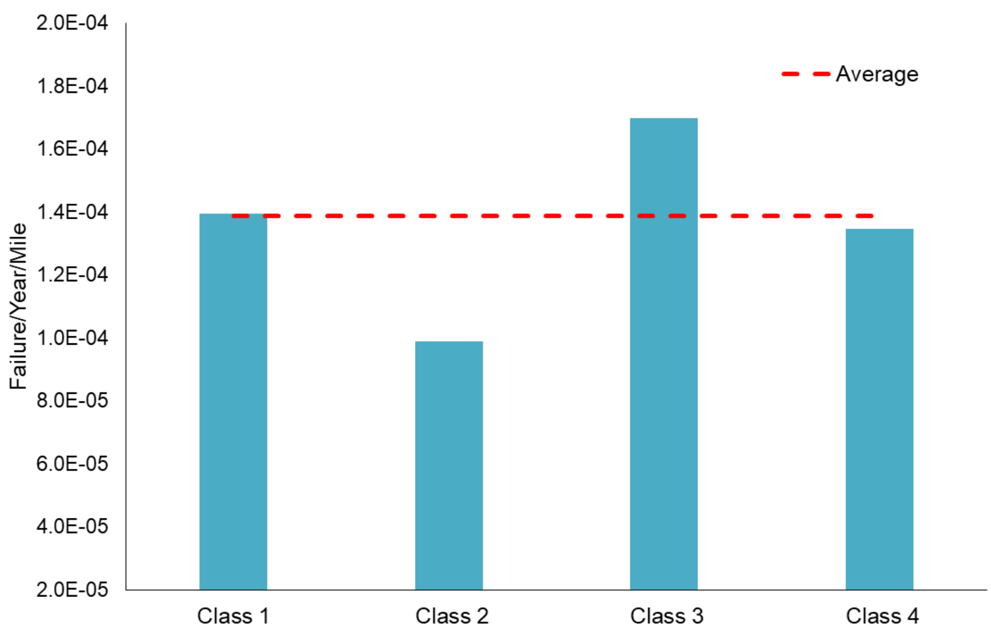


Figure 1. Natural Gas Transmission Pipeline Failure Rates by Class Definition

Using the USDOT natural gas transmission data for the 2010 to 2016 time period results in an average (over all Class types) natural gas release frequency of 1.39 $(10)^{-4}$ releases of natural gas transmission pipeline per mile per year.

Risk Acceptability Criteria

There are several measures of risk and the project proponent and the regulator must make decisions about the acceptability of risk in order to determine the acceptability of a pipeline project or pipeline route. There are different risk acceptability criteria for individual (a single person) and societal (multiple persons) risk measures.

The most common risk calculation made is for what is often called individual risk (IR). In all of the risk criteria to be discussed, it is the risk of fatality, not risk of exposure or risk of injury, which is defined. The risk of fatality is universal, while the definition of injury is not.

While the IR calculation may be made correctly, it is often interpreted incorrectly. Most IR calculations are actually the predicted risk to a location and not to a person. In order for the risk to a person to be equal to the risk at a location, the following would have to be true.

- The hazard endpoints (i.e., limits) would have to be defined for people not property.
- The person would have to stay at the specific location 24 hours a day and 365 days a year, in other words continuously for a full year.

Since most people do not stay in the same location continuously for a full year, the IR calculated is really the location specific individual risk (LSIR). The IR value for a person is never greater than the LSIR, and often can be quite a bit lower.

The LSIR for a pipeline is often presented in what is referred to as a risk transect. A risk transect presents the LSIR as it extends perpendicularly away from a pipeline. An example of an LSIR transect is presented in Figure 2.

A second risk measure is one that calculates the risk of one or more persons being killed due to an individual event. This is called societal risk since it measures the impact on more than one exposed person. Societal risk may be presented in the form of an F-N curve, where the y-axis is defined as F, where F is the cumulative frequency of N or more fatalities. The x-axis is N. An example of F-N curves (solid lines) is presented in Figure 3.

A project whose F-N curve lies above or extends into the area above the red line (for example, the dashed blue line in Figure 3) is deemed as unacceptable. This project will be rejected on the grounds that the risk to the public is too high, thus unacceptable.

A project whose F-N curve lies entirely below the below the green line (for example, the dashed orange line in Figure 3) is deemed as acceptable. This project should be accepted on the grounds that the risk to the public is low, thus acceptable. A project with an F-N curve entirely in the acceptable region would not require any additional risk reduction measures.

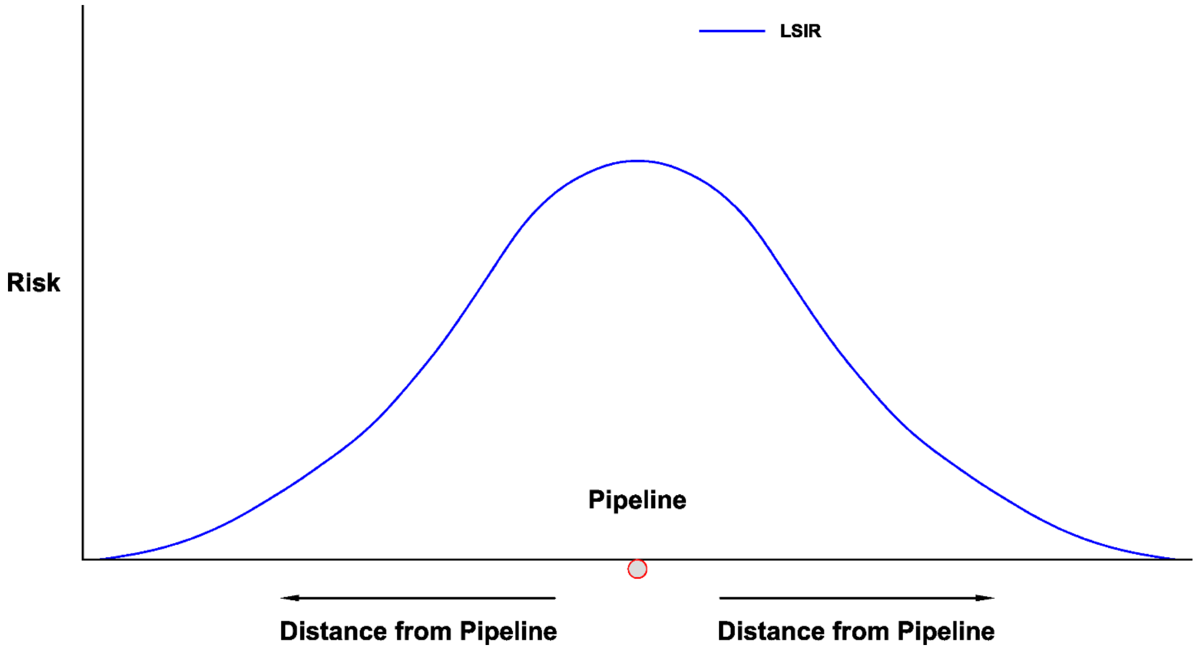


Figure 2. LSIR Transect for a Pipeline

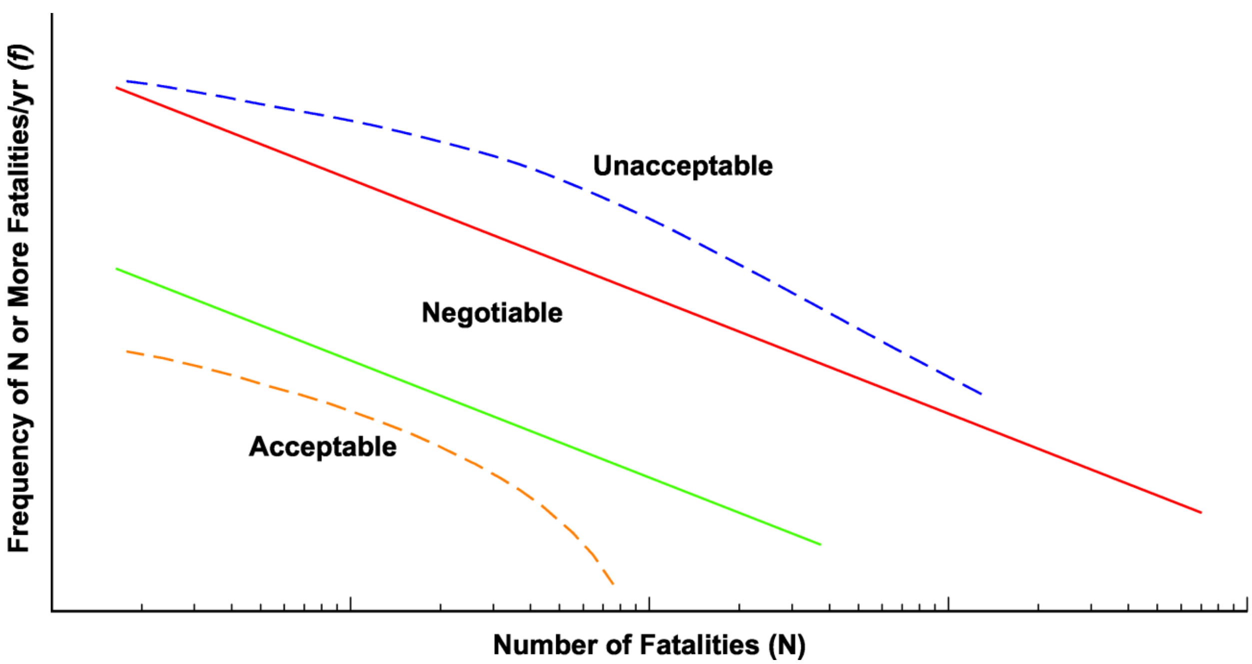


Figure 3. Form of an F-N Curve

Notice the area in Figure 3 between the two solid diagonal lines. The area between the lines is defined as negotiable. In some risk criteria, this area is called As Low As Reasonably Practicable (ALARP). The definition of reasonably practicable is described by the United Kingdom's Health and Safety Executive (HSE)[2] as

> "Reasonably practicable involves weighing a risk against the trouble, time and money needed to control it. Thus, ALARP describes the level to which we expect to see workplace risks controlled."

In other words, an F-N curve that lies within or partially within the two solid diagonal lines would require the project to lower the F-N risk curve to below the lower (green) diagonal line if reasonably practicable. The decision of whether enough risk reduction has been made such that further risk reduction is not reasonable practicable, is up to the regulator(s), thus the use of the term "negotiable."

For fixed or point facilities, the societal risk measure (F-N curve) works well since the assumption is that the population near the facility is clearly defined and constant. For pipelines, this type of measure can cause some degree of confusion as a pipeline may pass through an area without any resident population (risk = 0), but also pass through or by a populated residential area (risk > 0).

EXAMPLE RISK CRITERIA FOR NATURAL GAS TRANSMISSION PIPELINES

Individual Risk

As an example consider an onshore natural gas transmission pipeline. This pipeline is a 24-inch diameter pipeline that operates at 1,000 psig. The pipeline is buried by traditional trenching. A hole develops in a segment of the pipeline that is approximately 2 miles downstream of a compressor. The area where the release occurs has moderate humidity and 10-year average wind pattern as described in Figure 4.

The risk transect for the example onshore natural gas transmission pipeline is presented in Figure 5. As shown in Figure 5, the risk to persons in the area near the pipeline decreases as the distance from the pipeline increases.

If the one in a million ($1.0\ (10)^{-6}$) risk level is a value that is deemed an acceptable IR level for the public then the natural gas transmission pipeline would be deemed acceptable. Different countries (e.g., Australia, Mexico, Hong Kong, Brazil) use this risk criteria for IR. It should be kept in mind that the IR is defined to be risk of a fatality. Keeping in mind that the calculated risk is location-specific, the true risk to an individual at a distance from the pipeline is less than that shown.

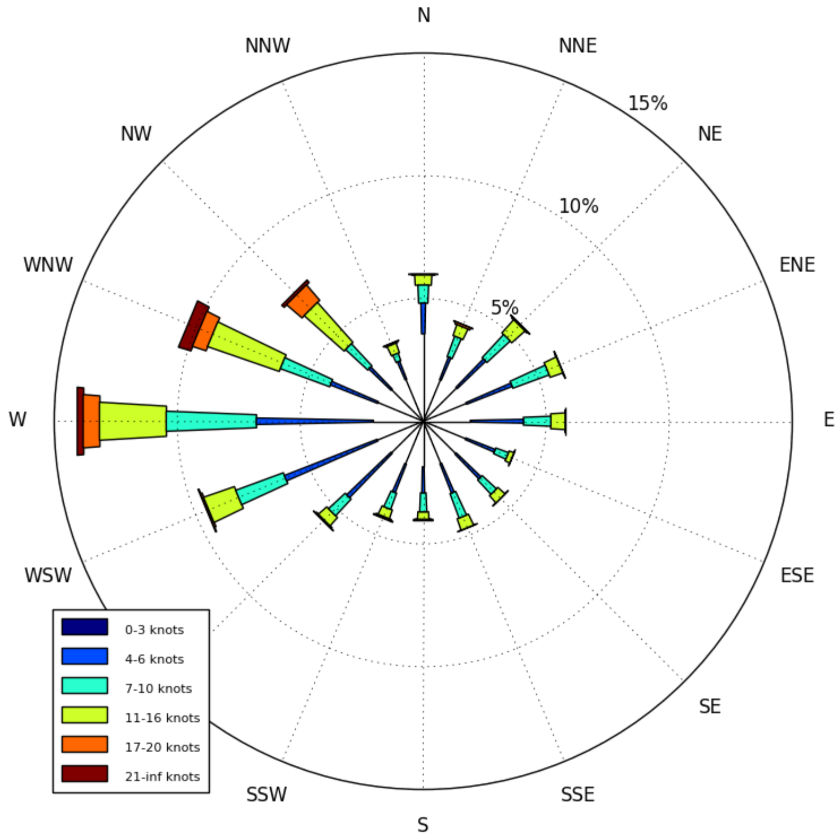


Figure 4. Wind Rose for Example Pipeline QRAs

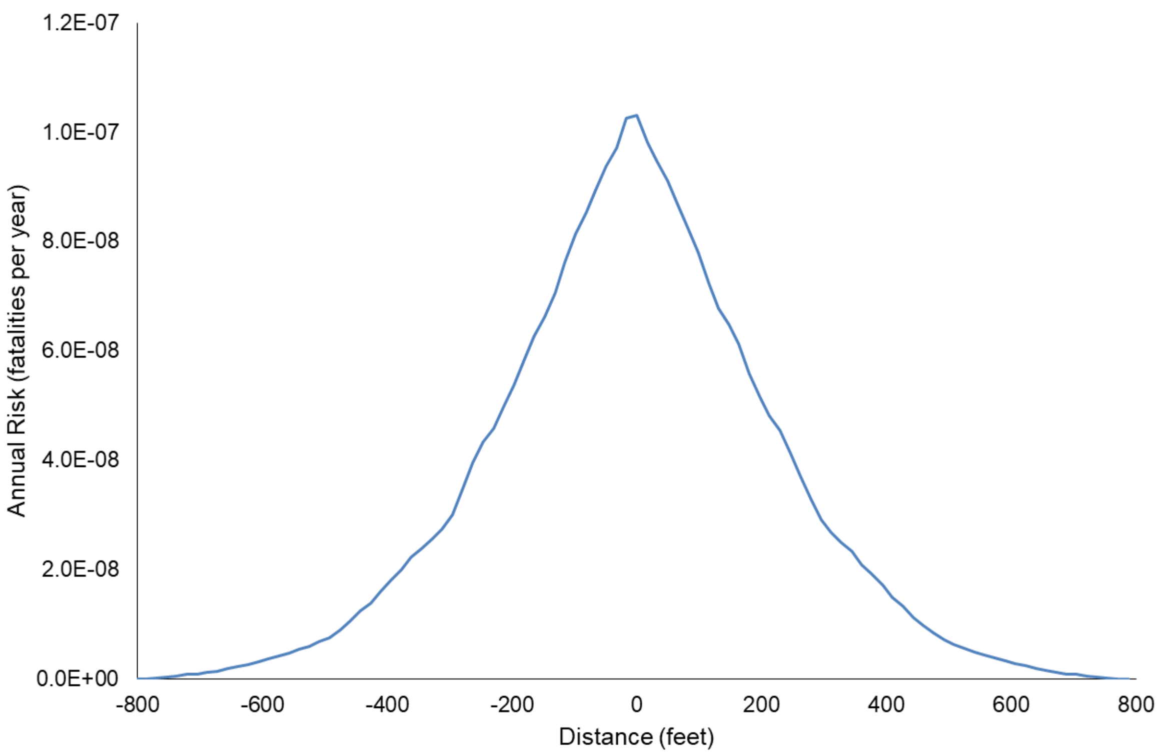


Figure 5. Risk Transect for Example Onshore Natural Gas Transmission Pipeline

Societal Risk

As described above, the population along a pipeline route may change and this causes the risk to the public along the pipeline to change as well. Using the USDOT pipeline classifications as a way to define the population provides a consistent, reproducible method to develop the risk along the pipeline. Using the maximum number of buildings in the one-quarter square mile area and the following assumptions

Each building is a residence
Each residence has 2.5 people[3]

Class 1	Maximum of nine buildings in the one-quarter square mile area.
Class 2	Maximum of 46 buildings in the one-quarter square mile area.
Class 3	More than 46 buildings in the one-quarter square mile area. Class 3 is evaluated by two population layouts for demonstration, Class 3a and Class 3b.
Class 3a	46 buildings per mile of pipeline
Class 3b	92 buildings per mile of pipeline
Class 4	Any Class 4 pipeline has to be analyzed on a site-specific basis

These population distributions are shown graphically in Figure 6. It should be noted that the buildings (i.e., houses) are located a minimum of 33 feet from the natural gas transmission pipeline. The 33 feet is designed to represent the right-of-way for the pipeline.

One method to evaluate the pipeline route allows each subject pipeline to be divided into segments (constant lengths of pipeline) and each segment evaluated and compared against established societal risk criteria. One-mile pipeline segments are selected because the USDOT pipeline classification system is based on the population along one mile of pipeline. Since the natural gas transmission pipelines that are the subject of this paper do not have any significant toxic components, a one-mile length of pipeline will not exclude the impact of any potential hazard (e.g., flash fire, jet fire, or explosion overpressure).

The societal risk F-N curve would be constructed for each one-mile section of pipe. The F-N curves for each one-mile section would be plotted against established societal risk criteria and each pipeline section's risk acceptability will be evaluated. In this example the British F-N criteria[4] are presented as the established societal risk criteria. The example natural gas transmission pipelines, by DOT Class designations, are plotted in Figure 7. As can be seen in Figure 7, as the number of buildings (and thus the number of persons) increases, the overall F-N curves move to the right (greater N). The low historical frequency of natural gas transmission pipeline failure keeps the F-N curves below the risk acceptability criteria.

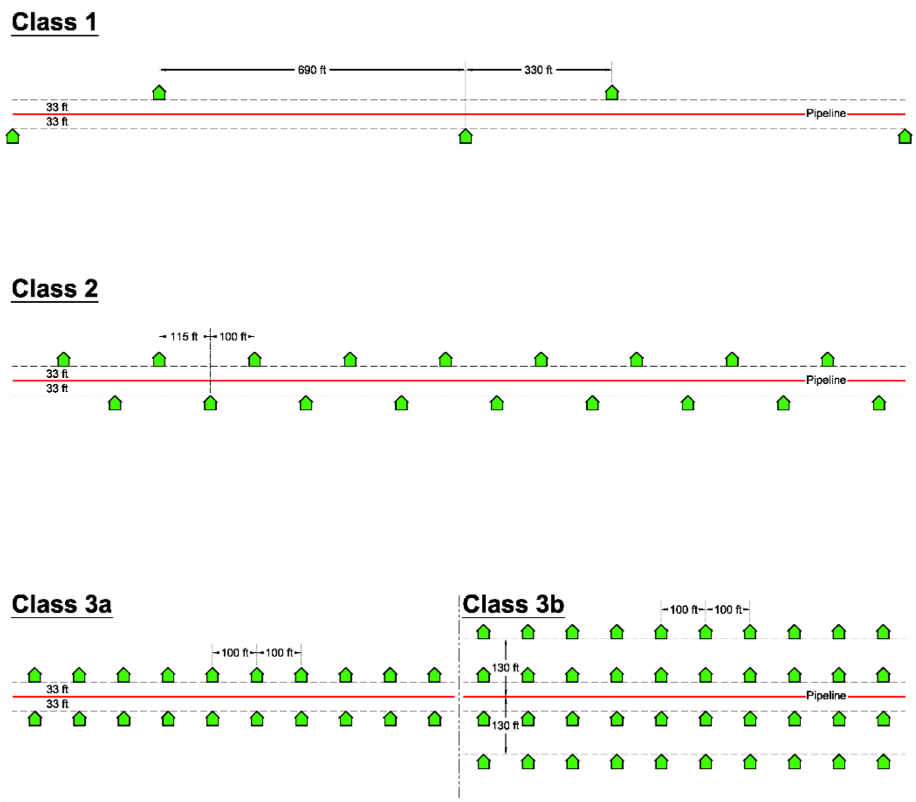


Figure 6. Example Building Distributions According to DOT Class Designations

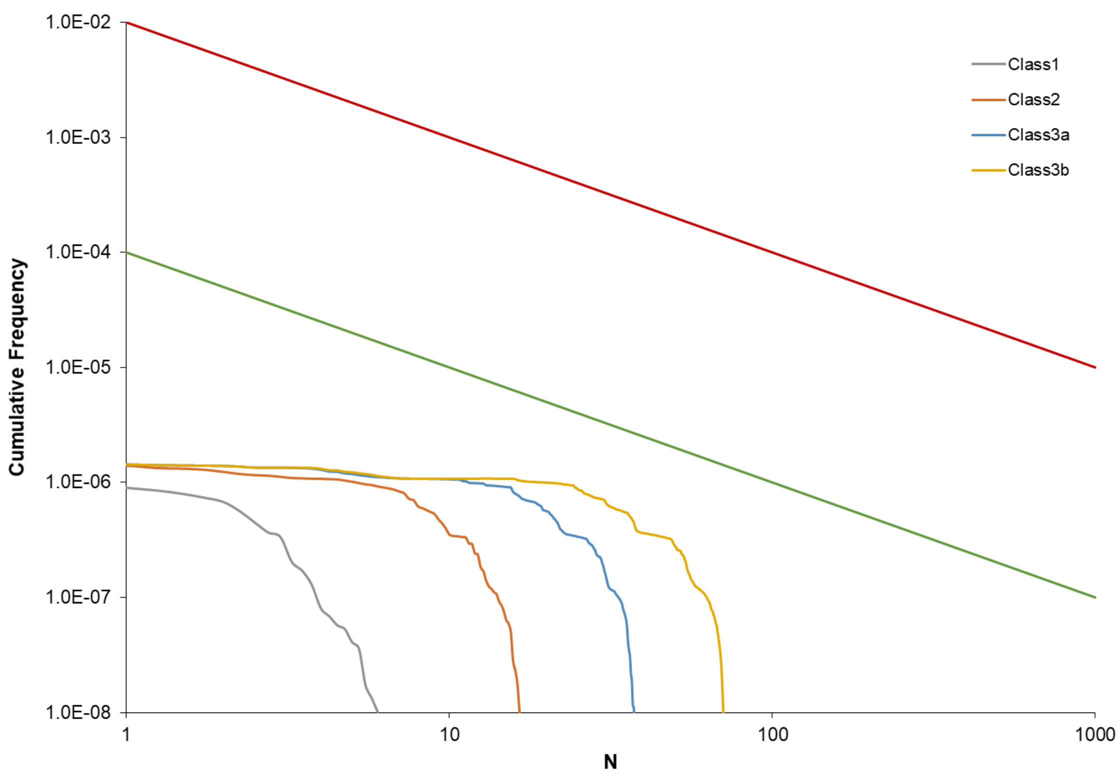


Figure 7. F-N Curves for Example Natural Gas Transmission Pipeline by DOT Class

As described above, what makes the risk calculations for a pipeline unique it the variability of the population along the route. In an effort to determine how sensitive the risk calculations (i.e., the F-N curves) are to the layout of the buildings along the pipeline route, several different Class 2 layouts were evaluated. These variations, using a constant population of 15, are identified on Figures 8 and 9 and can be summarized as follows:

- 15 persons parallel to the East-West (E-W) pipeline
- 15 persons perpendicular to the E-W pipeline
- 15 persons spread out near the right-of-way of the E-W pipeline
- 15 persons spread out far from the right-of-way of the E-W pipeline
- 15 persons parallel to the same pipeline when the pipeline is oriented North to South (this shows the impact of the wind rose relative to the pipeline orientation)

As can be seen by the F-N results presented in Figure 9, there are small differences in the calculated risk to the exposed public. When the people are located away from the pipeline (the yellow line), the risk is lower than when the people are located near the pipeline. In addition, the shape of the wind rose or the orientation of the pipeline relative to the wind rose makes little difference in the resulting F-N curve. The reason for this is that the dominate hazard from a natural gas transmission pipeline release is a torch fire and torch fires are not significantly influenced by the prevailing wind patterns.

Some analysts use a population density instead of discrete population maps. This can lead to significant errors in the risk calculations. Using a Class 2 building (population) designation as the basis, three population maps were evaluated. These three population distributions are presented in Figure 10. Each distribution has the same total number of persons (115) within the DOT Class definition area. The constant density methodology yields a population density of 115 people per mile of pipeline or 0.0000165 persons/ft^2 or one person every 60,605 ft^2.

When risk calculations are performed on the three DOT Class 2 population distributions shown in Figure 10, the F-N curves in Figure 11 result. When the population density distribution is employed, as shown in “Class 2 Density” portion of Figure 10, the people are separated by such large distances that it is mathematically impossible to kill a single person. Thus, the F-N curve for the constant density population does not reach the N=1 number of fatalities. Similar to Figure 9, varying the specific locations of the population within the Class 2 area does not make much difference in the calculated risk.

Historically, there have been failures of natural gas transmission pipelines that resulted in multiple fatalities. As shown above, the potential number of fatalities is affected by the people’s locations relative to the pipeline. Figure 12 presents the natural gas transmission pipeline fatality data collected over a 47-year period. As can be seen from Figure 12, most of the fatalities recorded over the 47-year period are either single fatalities (N=1), or small groups of fatalities.

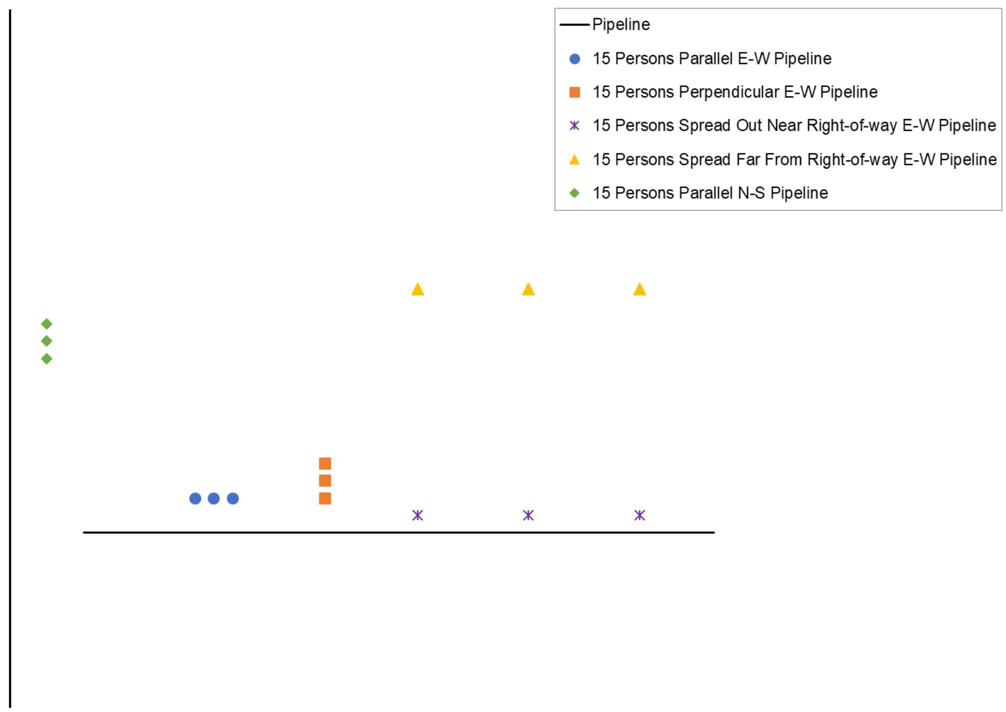
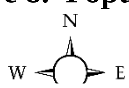


Figure 8. Population Distributions along Example Transmission Pipelines



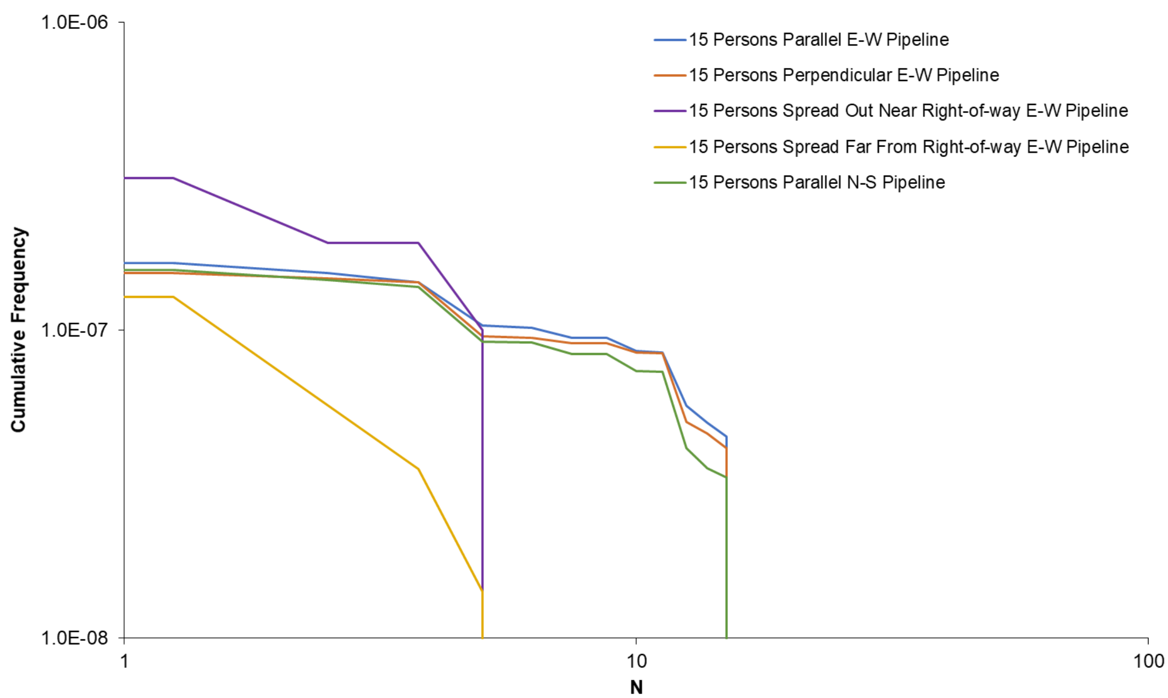


Figure 9. F-N Curves for Various Population Distributions

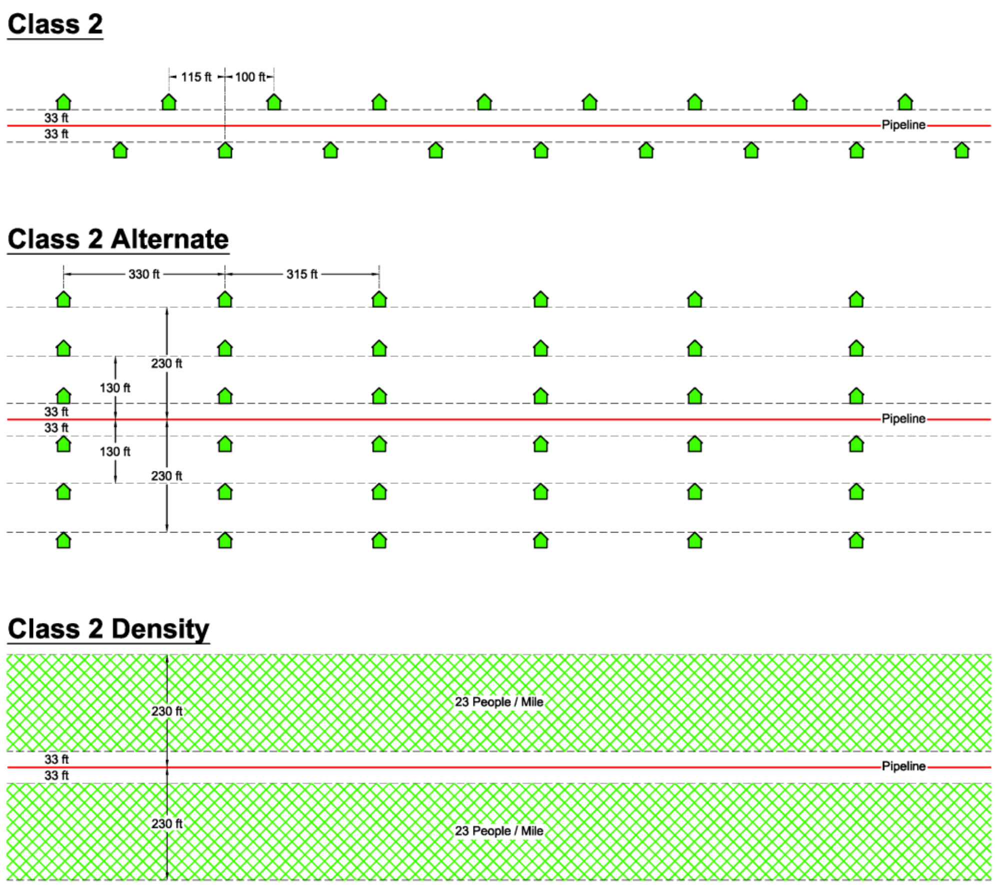


Figure 10. DOT Class 2 Population Distributions along the Example Natural Gas Transmission Pipeline (drawing not to scale)

There have been three natural gas transmission pipeline accidents that resulted in eight or more fatalities during this 47-year period. These are shown on the right-hand side of Figure 12 and described in Table 2.

The specific accidents listed in Table 2 could be modeled with the approach described above by locating a group or groups of people by the natural gas transmission pipeline. However, the frequency at which the specific event occurs (e.g., rupture of pipeline near bridge where people are camping for the night) would be so low that the single event may be acceptable according to the risk criteria.

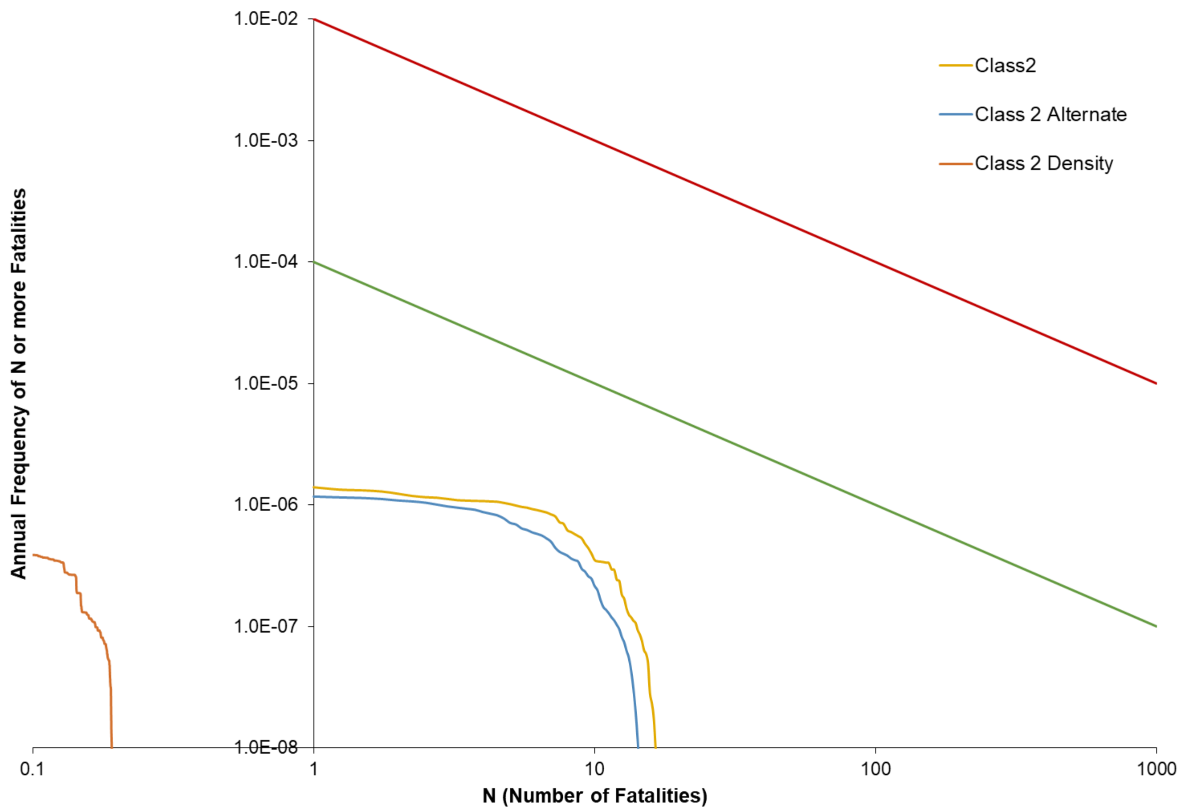


Figure 11. F-N Curves for Three DOT Class 2 Population Distributions

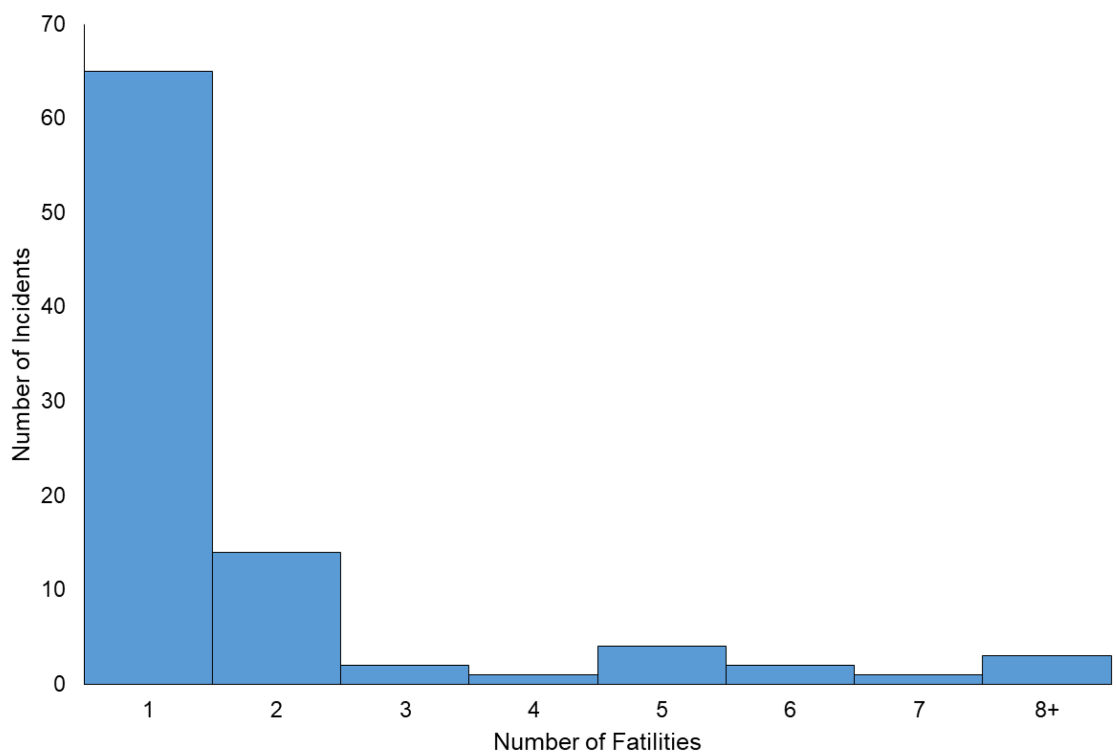


Figure 12. Historical Natural Gas Transmission Fatality Data from 1970 – 2016

Table 2. Historical Fatality Data for Eight or More Fatalities over a 47-Year Period

Date	Fatalities	Accident Description
10/3/1989	11	On October 3, 1989, the United States fishing vessel NORTHUMBERLAND struck and ruptured a 16-inch diameter natural gas transmission pipeline about ½ nautical mile offshore in the Gulf of Mexico, and about 5 1/3 natural miles west of the jetties and the entrance to Sabine Pass, Texas. Natural gas under a pressure of 835 psig was released. An undetermined source on board the vessel ignited the gas, and within seconds, the entire vessel was engulfed in flames. The fire on the vessel burned itself out on October 4. Leaking gas from the pipeline also continued to burn until October 4. Of the 14 crewmembers, 11 died as a result of the accident[5].
8/9/2000	12	At 5:26 a.m., mountain daylight time, on Saturday, August 19, 2000, a 30-inch-diameter natural gas transmission pipeline operated by El Paso Natural Gas Company ruptured adjacent to the Pecos River near Carlsbad, New Mexico. The released gas ignited and burned for 55 minutes. Twelve persons who were camping under a concrete-decked steel bridge that supported the pipeline across the river were killed and their three vehicles destroyed. Two nearby steel suspension bridges for gas pipelines crossing the river were extensively damaged[6].
9/9/2010	8	On September 9, 2010, about 6:11 p.m. Pacific daylight time, a 30-inch-diameter segment of an intrastate natural gas transmission pipeline known as Line 132, owned and operated by the Pacific Gas and Electric Company (PG&E), ruptured in a residential area in San Bruno, California. The rupture occurred at mile point 39.28 of Line 132, at the intersection of Earl Avenue and Glenview Drive. The rupture produced a crater about 72 feet long by 26 feet wide. The section of pipe that ruptured, which was about 28 feet long and weighed about 3,000 pounds, was found 100 feet south of the crater. PG&E estimated that 47.6 million standard cubic feet of natural gas was released. The released natural gas ignited, resulting in a fire that destroyed 38 homes and damaged 70. Eight people were killed, many were injured, and many more were evacuated from the area[7].

SUMMARY

The quantitative risk analysis methodology presented in this paper allows the user of the methodology to evaluate the individual and societal risk associated with natural gas pipelines. The individual risk associated with pipelines has been the traditional method used to evaluate the risk associated with natural gas pipelines. The individual risk approach does not take population into account. As project proponents and regulators struggle to assess the risk associated with natural gas pipelines that are routed though populated areas, another risk measure is needed.

By the use of DOT Class definitions, converted to people instead of buildings, the risk associated with each pipeline section (this paper uses one-mile pipeline sections) can be evaluated. If a pipeline section is shown to extend into an unacceptable or negotiable region of the societal risk criteria (F-N curves) measures can be taken to lower the risk. These measures could include, but are not limited to, depth of burial, change of operating conditions, and rerouting part of the pipeline. With this approach the risk associated with any natural gas pipeline can be assessed.

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