

RISK MEASURES FOR PIPELINE SAFETY

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Abstract. In the present study, risk measures such as personal risk, expected loss, and F-N curves are compared against novel risk measures such as Value-at-Risk (VaR), Conditional Value-at-Risk (CvaR), and expected utility. Selected risk measures are assessed for their compatibility to use under two different decision-making conditions; (1) to demonstrate acceptable risk to external stakeholders, and (2) to optimize asset management. For this purpose, the selected risk measures are evaluated for (1) ease of risk aggregation across asset types and various consequence outcomes; (2) ability to transform risk results to represent multiple time horizons or physical extents; (3) minimizing uncertainty in the estimated risk measure; and (4) ability to apply life-cycle optimization approaches. Outcomes of this study are applicable to life-cycle risk assessment of other critical linear infrastructure such as highways, railways, and high-voltage electrical transmission lines.

1 INTRODUCTION

Quantitative risk measures for onshore natural gas pipelines are focused on life safety and were developed from historical use of individual and societal risk measures that are common in process safety industries [1]. The historical approach for life safety risk measures was based on a point-source of risk due to an industrial or nuclear facility and the hazardous events to the general public due to the industrial product releases. Therefore, the criteria are associated with the hazard foot prints surrounding the facility location and corresponding land-use development decision-making at the time of facility permitting. In contrast, natural gas pipelines, and any other critical linear infrastructure, may extend across continents and need the definition of risk measures with specific definitions of physical boundaries. Furthermore, for optimal life-cycle maintenance decisions of such infrastructure, the risk measures must represent a time horizon applicable for the estimated risk.

In the contexts outside of regulatory decision-making for land-use development, such as risk ranking of the assets, cost-benefit analyses of inspection and mitigation activities, and emergency preparedness, a wide range of risk measures can be contemplated. Ideally, such risk measures should be feasible to be estimated with high confidence, have a large numerical range to distinguish between the high, medium and low risks, are responsive to the changes in asset condition to determine the effects of risk reduction and are aligned with the asset management

plans for the physical system boundary and inspection and maintenance intervals.

The objective of the present study is to compare the safety risk measures from the pipeline standards against the emerging risk measures that focus on tail risks. For this purpose, three safety risk measures, which are personal risk, expected loss, and F-N curves, are compared against the three emerging risk measures from the financial industry, which are Value-at-Risk (VaR), Conditional Value-at-Risk (CvaR) and expected utility. As the purpose of risk quantification and risk measures vary among different stakeholders, the common requirements of pipeline safety risk measures are described first, before summarizing the interpretation and calculation of the proposed risk measures. Following the summary of risk measures, the suitability of risk measures for pipeline safety under four different requirements are discussed and compared. The study concludes with a numerical example demonstrating the computation and application of the risk measures to a hypothetical pipeline system, and recommended decision-making contexts for the risk measures.

2 PIPELINE SAFETY REQUIREMENTS

All engineered infrastructure carries a risk of failure due to unexpected loads that are outside the design bounds. In the case of pipelines carrying petroleum products, the interpretation of pipeline safety varies significantly due to the perceived risk transfer of a private enterprise, such as a pipeline company, to the general public despite regulatory bodies governing the safety requirements in many jurisdictions. Transmission pipelines are linear infrastructure that extend across multiple regions, which implies that not only are the pipelines subjected to hazards from diverse sources, but also that the impacts due to pipeline failure cannot be contained with land development zoning in a particular region. Furthermore, a significant portion of the transmission pipelines may function well beyond their design life. The following sections describe the components of the four key factors that influence the pipeline safety requirements.

2.1 Stakeholders

There are four key stakeholders interested in the acceptance of the pipeline safety risk. These are the 1) general public, 2) regulatory bodies, 3) pipeline integrity engineers, and 4) asset managers. The interest of the general public chiefly extends to the direct impact of pipeline failure on the areas that they occupy. The regulatory bodies have to set the safety requirements to ensure that there is net public good due to the pipeline infrastructure as well as a consistent demonstration of safety by all pipelines in operation. Pipeline integrity engineers are interested in risk measures that provide a rational and consistent tool for managing the pipeline safety and those that support optimizing the inspection and maintenance of the pipelines. Asset managers are interested in minimizing risk over a portfolio of various assets that may include pipelines, facilities, and virtual assets (e.g., databases, cybersecurity), posing a diverse set of risks. An ideal risk measure should address the interests of all of these stakeholders.

2.2 Risk sources

Pipeline risk is influenced by both asset-related and external factors. The asset-related factors are those that can be controlled by the asset owner through design, construction, operations, inspection and maintenance. These factors arise from latent manufacturing and construction defects, time-dependent threats such as corrosion and cracks, operational threats such as

overpressure events, and the hazardous nature of the products released in a failure event. External factors affecting the safety risk are unauthorized excavations on pipeline right-of-way, interference from high-voltage transmission lines, geohazards such as permanent ground movement and flood events, extreme events such as lightning and wildfires, changes to the land development, and an increase in population density near the pipeline right-of-way. These external factors are often difficult to control through pipeline integrity and asset management and may require interaction with other management systems. As such, the external factors increase uncertainty in the estimated risk measures.

2.3 Physical extents

Pipeline safety risk measures are often expressed as unit length of pipeline such as per kilometer or per mile. However, the extent of hazardous impact zones and risk mitigation efforts may occur at different scales. Typically, pipelines are inspected with inline inspection (ILI) tools over the segment of pipeline between a compressor or pump station to the next. The length of the pipeline segments may vary from 50km to 300km. The hazard impact zone due to ignited release of natural gas extends over a few meters with a typical range around 200m [2]. In contrast, the critical corrosion or crack defects that may lead to pipeline failure are limited at most to a pipeline joint of typical lengths between 12m to 30m. The physical extent of linear assets considered in the risk estimation would significantly affect the risk results due to an order of magnitude difference in the scale of risk factors. Risk measures that scale risk based on length would either inflate or mask the risk exposure.

2.4 Time horizons

Similar to the physical extents, the time horizon for the pipeline safety risk varies based on the risk source. For time-dependent threats to pipeline integrity, the increase in risk is influenced by the growth rate of the defects and the timing of the next inspection interval, which usually occurs between 5 to 10 years. For external factors such as land development and geohazards, the time horizons may occur over decades such as from 20 to 50 years. The decisions on operations and budget management may occur on an annual basis, and lead times for risk mitigation may vary between 2 to 5 years. As the uncertainty increases over longer time horizons, the misalignment between shorter inspection and risk mitigation time horizons with the longer-term effects may lead to increased exposure to chronic risks.

3 RISK MEASURES

3.1 Personal risk

Personal risk, also termed as individual risk, is the annual probability of fatality of a single person at a given location. This is also expressed as individual risk per annum (IRPA). If a person is assumed to be present at a given location 100% of the time, then the personal risk is also termed as 'location-specific individual risk' (LSIR). In both cases, the risk is a function of a given location. Figure 1 illustrates the differences in the individual risk with and without consideration of the chance of presence of an individual within the potential hazard zone.

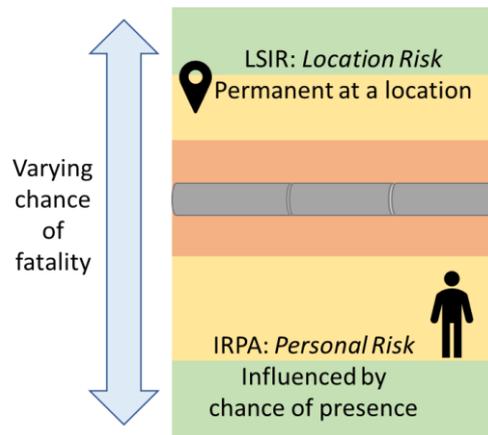


Figure 1: Personal risk and location risk

Equation (1) shows the approach to estimate the personal risk. The individual risk due to various hazards is assumed to be cumulative at a given location and the individual is assumed to acquire incremental risk due to the presence of the infrastructure that could potentially lead to a hazard.

$$IR = Pp \sum_{i=1}^n IR_i \quad (1)$$

$$IR_i = \sum_{j=1}^m P[I_i|H_j] \cdot P[H_j|E_i] \cdot P[E_i]$$

Where IR is the individual risk, Pp is the probability of presence of a person at a given location over a year, IR_i is the location-specific individual risk caused due to a failure event E_i that can result in a probability of hazard H_j , expressed as $P[H_j|E_i]$ and lead to a fatality event I_i with the conditional probability of fatality given a hazard, $P[I_i|H_j]$. Equation (1) indicates that individual risk includes the probability of fatality due to multiple different hazards triggered by the same failure event. This risk measure is used in the approvals for industrial facilities and land use development by evaluating if the incremental risk to an individual due to the approved facilities is tolerable [3].

3.2 Expected loss

Expected loss is the most commonly used risk measure as it is flexible to account for safety consequences in multiple units such as the number of fatalities, injuries, and dollar value. Equation (2) shows the calculation approach for expected number of fatalities, where the P_f is the probability of a hazardous event due to the pipeline failure and C is the consequence of the hazardous event expressed as fatalities.

$$EL = P_f \cdot C \quad (2)$$

Expected loss is a cumulative risk measure for all types of hazardous events and

consequences as long as the probability of the hazardous events is defined over the same physical extent and the time horizon, and the consequence is expressed in the same units. For comparison of the safety risks with other risks such as environmental risks and financial risks, the consequences are also expressed in terms of a dollar value by multiplying the number of fatalities with the value of a statistical life (VSL) [4]. Therefore, expected loss is also expressed in terms of safety costs for use in the cost-benefit analyses and the value of risk mitigation actions [5].

3.3 F-N curves

F-N curves are a representation of societal risk and express the cumulative occurrence frequency (F) of N or more fatalities. It can be interpreted as an inverse probability of exceedance curve. Figure 2 shows an example of the F-N curves derived for the number of fatalities from road, rail and aviation accidents in Great Britain from 1967 to 2001 [6]. The abscissa and ordinate are expressed in logarithmic scales to show low probability events.

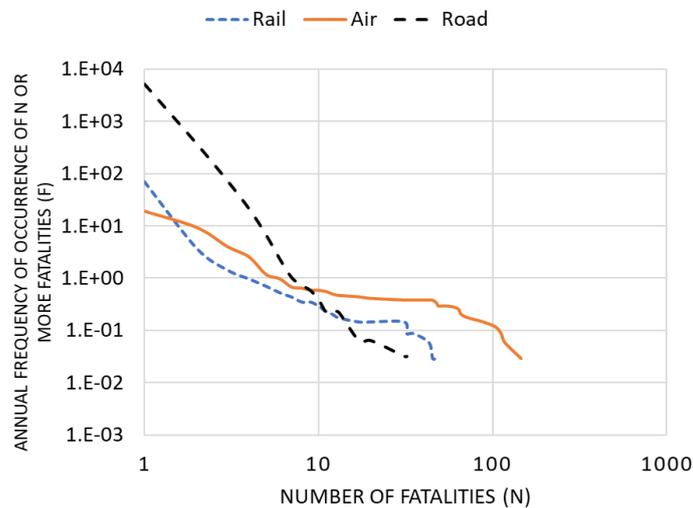


Figure 2: Example of F-N curves from road, rail and aviation accident data (recreated from [1])

While F-N curves are easier to derive from empirical data, their interpretation becomes difficult when consequences over different physical extents and time horizons are compared. F-N curves are usually estimated for industrial facilities where multiple hazardous events may occur with variable annual probability of occurrence and result in varying hazard impact zones. The F-N curves are then compared against the tolerance criteria for societal risk. Figure 3 shows an example of F-N curves from benchmark studies of two liquefied natural gas (LNG) facilities that are compared against the tolerance criteria represented as the shaded areas [7]. The shape of the F-N curves informs if the risk sources are from high frequency low consequence events or from low frequency high consequence events. The red shaded area represents intolerable risk while the green area represents the broadly acceptable risk. The risks in the yellow shaded area are conditionally tolerable if they are demonstrated to be as low as reasonably practicable ('ALARP').

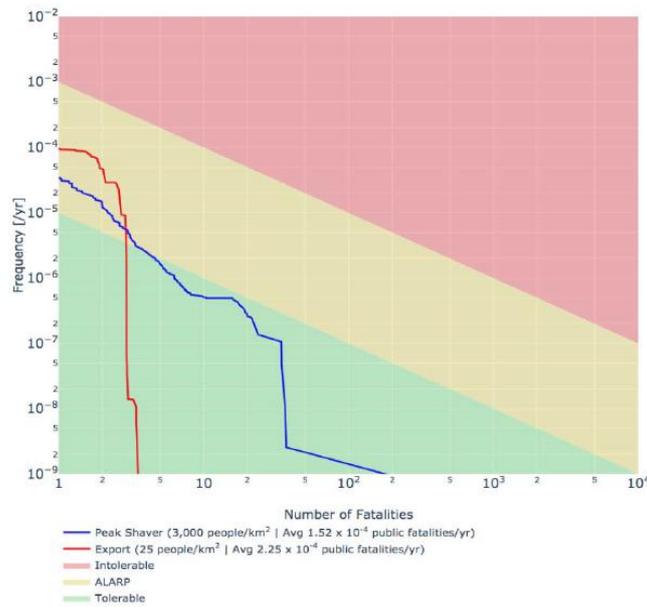


Figure 3: Example of F-N curves from LNG facilities (from [7])

3.4 Value-at-Risk

Value-at-Risk (VaR) is defined as a percentile value of the probability distribution of the loss [8]. This definition treats loss as a probability distribution with its own uncertainty rather than a single value as is the case with the expected loss. This approach of estimating a complete distribution of losses enables explicit consideration of uncertainties in the consequence estimation arising after a pipeline failure event. As this risk measure is not previously used for safety risk, the choice of percentiles to estimate VaR are not readily available. Equation (3) shows the VaR defined at α percentile value of the probability distribution F_X representing the consequences X .

$$VaR_\alpha = \min \{z \mid F_X(z) \geq \alpha\} \quad (3)$$

3.5 Conditional Value-at-Risk

Conditional Value-at-Risk (CVaR) is the expectation of the probability distribution of the loss that is above a percentile value. The tail probability distribution of the loss, that is above the chosen percentile value, is normalized to represent a complete random variable distribution. For a discrete distribution of losses, CVaR can be defined as a weighted average of the losses exceeding VaR, which is weighted by the proportion of events that contribute to the exceedance of VaR. Equation (4) shows the relationship between the CVaR and VaR for the α percentile value of the loss distribution F_X [8].

$$\begin{aligned} CVaR_\alpha &= \lambda \cdot VaR_\alpha + (1 - \lambda) \cdot E[X \mid X > VaR_\alpha] \\ \lambda &= (F_X(VaR_\alpha) - \alpha) / (1 - \alpha) \end{aligned} \quad (4)$$

3.6 Expected utility

Utility is a measure of preference under decision-making context. A utility function defines the attitude towards tolerance of loss. Using the expected value of the utility as a risk measure enables the inclusion of the decision-makers preference for the aversion of high consequences. If $U(X)$ is a utility function with respect to the loss X , then the computation of the expected utility is shown in Equation (5) where F_X is the cumulative distribution function of loss [9].

$$E_u = \int U(z) \cdot F_X(z) \cdot dz \quad (5)$$

The utility function can be risk attracting, risk neutral or risk averse depending on the value of losses. Figure 4 shows an illustrative example of utility function that is risk attracting at low consequences, risk averse at high consequences and risk neutral in-between.

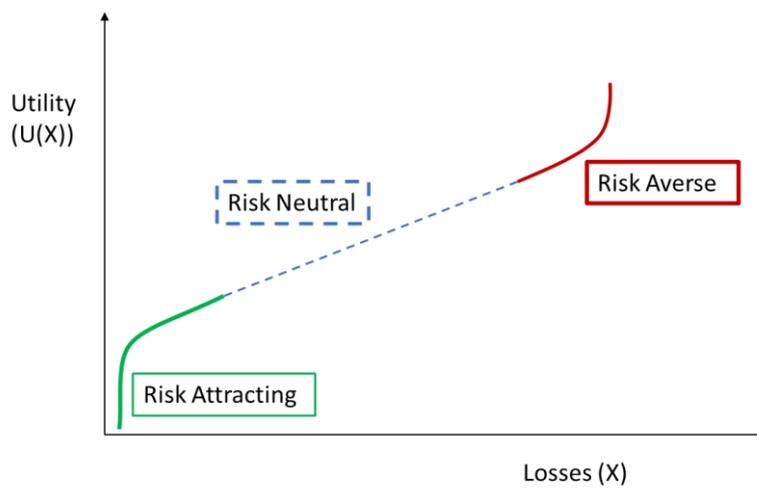


Figure 4: Utility function with risk attracting, risk neutral and risk averse relationship

4 COMPARISON OF RISK MEASURE SUITABILITY

4.1 Risk aggregation

As discussed in Section 2.2, pipeline safety risk can be affected by asset-related and external factors that contribute to both the likelihood and severity of the consequences. The personal risk and the expected loss risk measures provide the easiest approach to aggregation by summation. As the personal risk is defined by a particular location from the perspective of the risk receptor, the risk can be directly be aggregated as long as the consequence severity is consistently estimated. Similarly, expected loss is the easiest risk measure to aggregate losses from multiple hazards, across asset types and consequence severity as long as the units for measuring the consequences are consistent. F-N curves are the most difficult risk measure to aggregate risks from multiple sources as the scale of the curves could have large variation and may be difficult to interpret. Three risk measures, VaR, CVaR and expected utility were developed for aggregation of risks across multiple assets. However, it is acknowledged that VaR is not a well-behaved risk measure for aggregation [9].

4.2 Risk scaling

As the pipeline safety risk can be influenced by consideration of risks over various physical extents and time horizons discussed in Section 2.3 and 2.4, risk measures that have flexibility to be transformed across spatio-temporal axes are preferred in pipeline safety risk management. Expected loss presents the most flexibility to transform the risk between the physical extent and time horizons due to aggregation through summation. In contrast, personal risk is the most challenging risk measure as it is defined for a specific location. All other risk measures can be scaled based on the definitions of physical extents and the time horizons used in the generating the probability distributions of loss. However, once the risk measures are computed, it may be difficult to de-aggregate the risk over spatio-temporal axes if risk measures such as F-N curves, VaR, and CVaR are used.

4.3 Address risk uncertainty

Although risk is calculated under the assumption that losses under any given scenario are well-defined, that may not always be the case. The severity of the consequences can be sensitive to external factors such as product release conditions, weather conditions, and presence of individuals within the proximity of release. This introduces the uncertainty in the estimated risk measures if the possible variation of these conditions is not included. For this reason, expected loss has the most uncertainty in the estimated values as the risk analysis focuses only on the inclusion of expected values for the consequences. CVaR presents the least uncertainty in the risk measures as the variability in the severity of consequences is included as the distribution of losses and the tail-risks are aggregated to account for extreme events.

4.4 Life-cycle optimization

Optimizing for pipeline safety over all pipeline life-cycle phases such as planning, design, construction, commissioning, operations and maintenance provides the best option for improved safety. The cost-benefit analyses of risk mitigation over different life-cycle phases requires that risk measures can be compared for risk-informed decision-making across life-cycle stages. Expected loss is commonly used for optimization analyses due to the ease of comparison between risk scenarios and the ability to quantify the changes to risk due to optimization actions. Expected utility is also used in optimization for risk mitigation while including the risk preference of the decision-maker. However, due to the interests of multiple stakeholders in pipeline safety, the risk neutral approach might result in similar outcomes as the expected loss. CVaR provides the opportunity to address the tail-risks at initial life-cycle stages and monitor the changes to tail-risk with the progression of the life-cycle stages.

5 NUMERICAL EXAMPLE

5.1 Asset description

A hypothetical pipeline of 1km length was chosen from the literature to illustrate the computation of pipeline safety risk measures [10]. The pipeline was assumed to have 100 corrosion features distributed at a density of one per 10m length. The population density was assumed to be 0.32 people per hectare and a potential impact radius of the hazard zone due to

ignited release of natural gas is assumed to be 200m. The probability of fatality within the hazard zone is considered as 100%. The utility function was assumed to be risk averse, with the increase in loss as a square of loss value when the expected number of fatalities exceed 1.0. The value of statistical life is assumed to \$10,000,000. Figure 5 shows the distribution of the probability of ignited release due to each corrosion feature along the pipeline chainage. The probability of presence of an individual at the location of the pipeline was randomly generated over a uniform distribution between the bounds 0.0 and 1.0. The distribution of the probabilities generated are also shown in Figure 5.

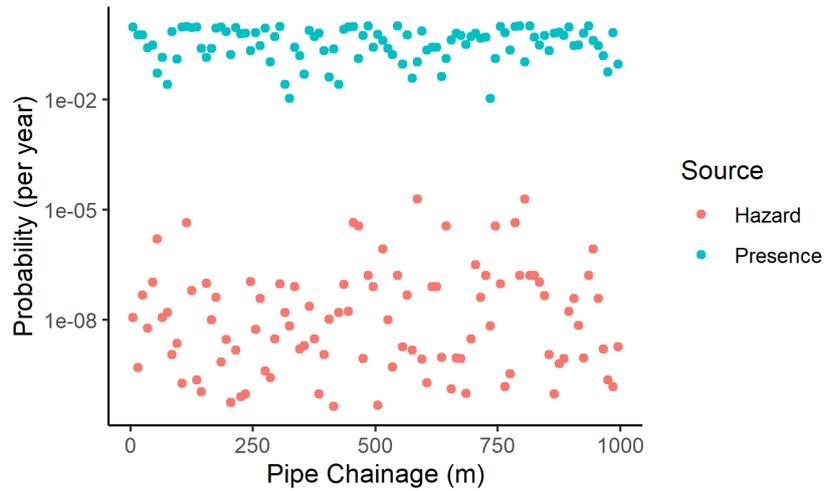


Figure 5: Distribution of probability of hazard and population presence along the pipeline

5.2 Risk measures

The six risk measures discussed in Section 3 were computed for the hypothetical pipeline. Table 1 shows the scalar risk measures, which are expected loss, VaR at 90th percentile, CVaR at 90th percentile and the expected utility.

Table 1: Risk measures

Risk Measure	Value (in average number of fatalities)	Value (in \$)
Expected loss	8.47E-05	847.25
VaR90	8.59E-07	8.59
CVaR90	7.67E-05	766.77
Expected utility	2.51E-04	2509.33

Figure 6 shows the personal risk and the location-specific individual risk along the pipeline length. As the personal risk includes the probability of individual presence, the individual risk represented by the personal risk is lower than the location-specific individual risk. Figure 7 shows the F-N curve generated for the 1km pipeline with expected number fatalities, N, truncated to be greater than or equal to 1.0. As the population density was assumed to be uniform along the pipeline, the maximum value of expected number of fatalities (N) is influenced directly by the variation in the probabilities shown in Figure 5.

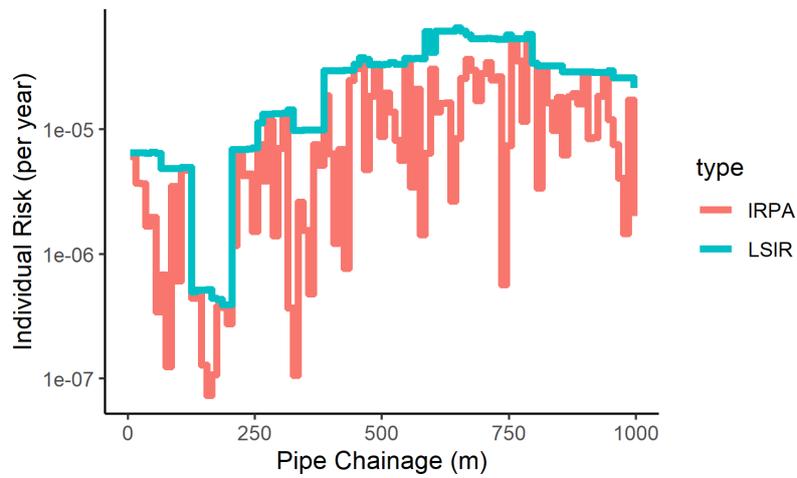


Figure 6: Individual risk along the pipeline

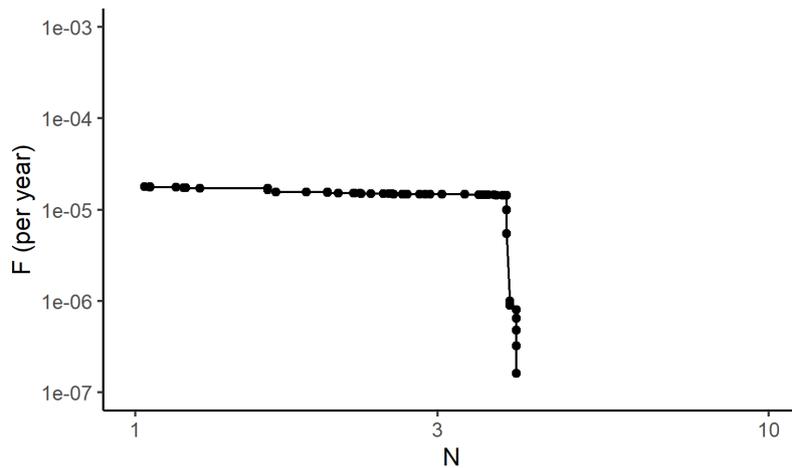


Figure 7: F-N curve of hypothetical pipeline

5.3 Discussion

Of the six risk measures computed, personal risk and F-N curves have risk tolerance criteria available in the pipeline standards. These criteria may be applied to identify risk mitigation actions such as remediation of the corrosion defects. In several international standards, personal risk exceeding 10^{-4} per year (or 1 in 10000) is considered as intolerable for the general public. As the maximum value of personal risk is 5.6×10^{-5} per year, the personal risk is considered to be conditionally tolerable if the risk is demonstrated to be the ALARP. However, the expected loss in dollar value is less than \$1000 while the remediation costs are typically around \$200,000. The grossly disproportionate cost-to-benefit ratio indicates that the safety risk is tolerable.

As there are no uncertainties considered in the estimated of the number of fatalities,

population density and the probability of fatality, the risk measures of VaR and CVaR are consistent with the expected loss values. In contrast, the risk aversion included in the utility function had significant effect on the expected utility. However, due to the assumption of a well-maintained pipeline in a sparsely populated area, the overall risk is within tolerable limits.

The risk measures were all quantified on an annual basis over the pipeline length, which masked the distinction between the outcomes of the risk measures. If the risk is estimated over a longer time horizon, then uncertainties in the corrosion growth rates and variability of growth among corrosion features would have significant impact on the tail risk, and consequently on VaR and CVaR. However, as there are no established risk tolerance criteria for risk measures such VaR and CVaR and given the high aversion to safety risk due to pipeline failures, it is difficult to demonstrate if the safety risk at the percentile values chosen for VaR and CVaR would be tolerable.

6 RECOMMENDATIONS

The selected risk measures when assessed against the pipeline safety requirements have advantages and challenges related to the decision-making context. For established risk measures such as personal risk and F-N curves, it is easier to demonstrate the safety by comparing the risk measures against the available tolerance criteria. However, these measures, particularly F-N curves, are not suitable for decision-making contexts for risk mitigation and cost-benefit analyses. Furthermore, due to annualized nature of personal risk and F-N curves, they are a reflection of average annual risk that do not highlight time-dependent increase in risk. In such cases, scalar risk measures such as expected loss and CVaR are suitable. It is easier to demonstrate cumulative risk over varied physical extents and time horizons with expected loss and CVaR. While expected utility can include the risk preferences of an enterprise, it has limited applicability for risk communication and life-cycle optimization for risk mitigation.

Future research is recommended to develop theoretical and empirical relationships between the risk measures. This would enable stakeholders to use appropriate risk measure for specific decision-making contexts while being consistent in the interpretation of the implied safety. Table 2 shows the recommended risk measures for different stakeholders and their decision-making contexts.

Table 2: Recommended risk measures

Stakeholders	Most Useful	Least Useful
General public	Personal risk	Expected loss
Regulatory bodies	F-N curves	Expected utility
Pipeline integrity engineers	Expected loss	F-N curves
Asset managers	CVaR	F-N curves

7 CONCLUSION

In the present study, six risk measures were selected to represent pipeline safety risk and evaluated for (1) ease of risk aggregation across asset types and various consequence outcomes; (2) ability to transform risk results to represent multiple time horizons or physical extents; (3) minimize uncertainty in the estimated risk measure; and (4) ability to apply life-cycle

optimization approaches. The discussion shows that the different risk measures are suitable under different decision-making contexts. The key recommendation for future work is to establish the relationship between the risk measures in practical contexts such that the same risk assessment results can be used to address multiple stakeholder safety requirements.

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