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Sensitivity of Optimal Decision Outcome to Consequence Assumptions in Value of Information Analysis

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ABSTRACT: Value of information is directly related to the expected reduction in cost of consequences due to the availability of the inspection information. However, the estimation of consequence cost can be highly variable due to consequences that are difficult to quantify such as safety costs, reputational costs, regulatory costs, and impact on societal license for future business development. While the intangible costs are difficult to quantify with precision, the range of possible costs can be estimated from previous events and the other business cost estimates. Inclusion of this possible range for cost of consequences, instead of single value of best estimate, provides additional insight for decision-making using the value of information analysis. This study presents the approach for a buried natural gas transmission pipeline. The cost paradigm considers the failure consequence costs at a component level and system level for the transmission network, and impact of the uncertainty in the failure costs due to the scale of the system considered is presented. A numerical example is presented to demonstrate the decision-outcomes with consideration of the cost uncertainty.

1. INTRODUCTION

In the optimization of life-cycle management of infrastructure elements, inspection and maintenance planning has a significant role in assessing the cost-benefit trade-off. While maintenance activities reduce the potential for further degradation and the likelihood of failure, scheduling maintenance activities for non-critical components of the system leads to non-optimal usage of resources. On the other hand, while inspection activities could improve certainty of the degradation status of various components of the system, they do not reduce the inherent likelihood of failure. The decision-making challenge between scheduling inspection and maintenance activities is generally addressed through a value of information analysis and the expected benefit due to inspection.

The value of information obtained through an inspection activity is influenced by a variety of factors, including: (1) uncertainty in the current system status due to availability, completeness, and precision of the system parameters as well as the uncertainty of the degradation mechanisms; (2) performance of the available inspection methods and the expected reduction in uncertainty of the system status; and (3) cost of inspection and cost of failure including the effect of location and time of failure. Therefore, the estimated expected benefit due to the inspection will be influenced by the prior status of these factors.

In the literature, previous studies on the sensitivity analysis of the expected benefit of inspection were focused on the system status as represented through parameter uncertainty and temporal uncertainty due to degradation mechanisms (Khan et al. 2020, Di Francesco et al. 2021, Yuan et al. 2021). In the present study, the objective is to estimate the benefit of an inspection program given the uncertainty in the cost of failure on a buried natural gas transmission pipeline. Ignition of released natural gas from high-pressure transmission pipelines pose significant safety risk to the population around the pipeline. However, in addition to the safety costs, the pipeline operator may suffer downtime cost until service restoration, reputational costs due to public impact as well as regulatory costs due to increased scrutiny. These costs are difficult to estimate solely from historical data as they are partly influenced by the societal license for pipeline operation.

In the present study, sensitivity of the benefit of inspection is analyzed considering the uncertainty in the failure costs of a buried natural gas pipeline. The benefits of inspection at a component level, such as a single pipeline segment, and at the system level are estimated. The sensitivities of the estimated benefit at the component level and system level are compared to highlight the influence of the scale of the system on the expected benefit of inspection. In particular, the benefit of system-level inspection planning and the importance of system-level inspection prioritization compared to component level failure costs is demonstrated.

2. METHODOLOGY

2.1. *System Description*

Natural gas transmission pipelines traverse multiple terrains across thousands of kilometers and have exposure varying levels of consequences based on the location of failure event. The section of pipeline between two compressor (or pumping) stations is termed as a ‘pipeline segment’ and is on average about 100km in length. A transmission system consists of multiple pipeline segments connected in series and may range over 1000kms or more. Due to the series connection of the pipeline segments, the failure event on any one segment is treated as independent of any other segment. Furthermore, inspection planning is often focused on prioritizing the pipeline segments to inspect.

The consequences of failure pipeline segment are related to the population density within the impact radius of the jet fire due to an ignited gas release. In North American pipeline design, there are four location classes designated based on the permanent structures within the impact zone, from Class 1 (with least population) to Class 4 (with high density population). The cost of failure on a pipeline segment is treated as a function of the location class due to the indirect consideration of the safety consequences related to population density.

Although safety consequences due to a failure event on a pipeline segment can be treated as independent of other potential failure events due to localized nature of jet fire events, the consequences to reputation, regulatory oversight and other business impacts have cumulative impact on the total failure costs. The simplified value of information framework is proposed in this study to account for this cumulative impact.

2.2. *Value of Information (VoI) Framework*

The expected value of information is generally characterized as

$$VoI = C_p - C_{pp} \qquad [1]$$

Where VoI is the value of information, C_p is the cost prior to inspection and C_{pp} is the pre-posterior estimate of the cost after inspection. The approach to estimate the prior and pre-posterior costs depends on the objective of the VoI analysis. For the integrity management of the pipelines, the relevant decision options are:

1. Inspection program to address a pipeline threat that has considered to have low susceptibility and has no standardized process for inspection or assessment. In this case, the prior costs will be solely due to cost of failure as there is no cost associated with the standardized inspection process. The pre-posterior estimate would include consideration of the detection, identification and severity estimation performance of the inspection approach or tool under consideration to estimate the costs of remediation and residual cost of failure.
2. Inspection program to consider a novel inspection methodology other than the standardized process. In this case, the prior costs will be due to inspection costs of the ongoing standardized process, and the cost of failure due to the performance deficiency of the standardized approach. The pre-posterior estimate would include similar considerations to the first option listed above in terms of the inspection performance in identifying the critical defects to pipeline integrity.
3. Determination of re-inspection interval following an initial inspection program. In this the prior costs would include cost of remediation of the defects identified during the initial inspection due to the uncertainties in the defect growth, the cost of failure due to the newly initiated or undetected defects, and rarely, the cost of failure due to imperfectly remediated defects. The pre-posterior costs would include cost of remediation following the re-inspection. In this case, the value of inspection will be a function of duration from the initial inspection.

In the present study, the scope is limited to the first option where there is no standardized system-wide inspection process and the initial consideration of the inspection program is being evaluated. The prior costs are modelled as

$$C_p = C_f \cdot N^{\alpha} \qquad [2]$$

Where C_f is the cost of a single failure event, N is the expected number of failure events and α is the cumulative impact of intangible business costs due to reputational and regulatory impacts for $N > 1.0$. While a one-off event may not attract severe regulatory impact, consecutive failures on the same pipeline system would indicate hidden process failures and attract increased scrutiny. The uncertainty in the cost of a single failure event itself will be addressed in the next section.

The expected number of failure events are estimated based on the probability of failure of any one defect on a pipeline segment, and the expected number of defects on the pipeline length considered. This is formulated as,

$$N = \sum_i \left(P_{fi}\ (g \leq 0) \cdot \rho_i \cdot L_i\right) \qquad [3]$$

Where P_{fi} $(g \leq 0)$ is the probability of failure of any single defect on a pipeline segment i, g is the limit state function representing the difference of burst pressure capacity to the internal pressure, ρ_i is the density of the defects per unit length of pipeline segment i, $L_p = \sum_i L_i$ is the total length of pipeline under consideration and L_i is the length of each pipeline segment.

In order to estimate the pre-posterior costs, the performance of the inspection tools must be known. Pipelines are inspected with inline inspection (ILI) tools of various technologies (magnetic flux leakage (MFL), Ultrasonic (UT), Electro-Magnetic Acoustic Transducers (EMAT), inertial measurement units (IMU)) to identify metal loss, cracks and other damage features in the pipeline that may lead to the burst of pipeline under operating pressures. The ILI tool performance metrics are defined as probability of detection (PoD), probability of correct identification (PoCI), and sizing uncertainty. Di Francesco et al. (2021) discusses the impact of probability of detection (PoD) and sizing uncertainty in the crack inspection tool on the variation of VoI. In this study, for simplicity, the ILI tools are assumed to provide perfect detection, identification and sizing of the defects similar to the formulation in Konakli et al. (2016). Therefore, the preposterior analysis for the cost estimate results in,

$$C_{pp} = C_r \cdot N_r + C_f \cdot N_d^{\alpha_d} + C_f \cdot N_{ud}^{\alpha} \qquad [4]$$

Where C_r is the average cost of a single repair, N_r is the expected number of repairs, N_d is the expected number of failures arising from detected defects that were not repaired, and N_{ud} is the expected number of failures due to undetected defects. α_d and α are respectively the component factors for detected and undetected cracks, which must be defined separately because of reputation costs associated with the failure of detected cracks may vary from those of the undetected cracks.

The expected number of repairs are estimated based on the population of defects that meet the detection criteria of the ILI tools and also meet the repair criteria. Typical detection criteria for ILI tools are set based on the defect depth and length. The standard repair criteria may depend on the defect depth and the tolerance threshold for the probability of failure. If the repair criterion is based on a tolerance threshold for allowable probability of failure per unit length of pipeline, P_{fa}, then, the expected number of repairs are estimated as,

$$N_r = \sum\nolimits_i (P_{fp} - P_{fa}) \cdot L_i^{in} \quad \text{where } P_{fp} \geq P_{fa} \qquad [5]$$

Where

$$P_{fp} = P_{fi}(g \leq 0 \mid s \geq S) \cdot p_d \cdot \rho_i \qquad [6]$$

P_{fp} is the proportion of cracks that exceed repair criterion per unit length of a segment, P_{fi} ($g \leq 0 | s > S$) is the conditional probability of failure of any single defect that exceeds the sizing threshold S to meet the detection criteria in pipeline segment i, p_d is the proportion of detected defects for the estimated distribution of defect sizing, and $L_{inp} = \sum_i L_i^{in}$ is the total inspected length of a pipeline, and L_i^{in} is the length of each inspected segment. If the repair criterion is not met, then the expected number of failures from unrepaired detected defects is estimated as,

$$N_d = \sum\nolimits_i P_{fdi} \cdot L_i^{in} \qquad [7]$$

where $P_{fdi} = P_{fp}$ for $P_{fp} < P_{fa}$, and $P_{fdi} = P_{fa}$ for $P_{fp} \geq P_{fa}$.

The expected number of failures due to undetected defects are estimated as,

$$N_{ud} = \sum\nolimits_i (P_{fi}(g \leq 0 \mid s < S) \cdot p_{ud} \cdot \rho_i \cdot L_i^{in}) + \sum\nolimits_i (P_{fi}\ (g \leq 0) \cdot \rho_i \cdot L_i^{un}) \qquad [8]$$

Where p_{ud} is the proportion of undetected defects on the inspected pipeline such that $p_d + p_{ud} = 1.0$, and $L_{pun} = \sum_i L_i^{un}$ is the total uninspected length of pipeline, and L_i^{un} is the length of each uninspected segment. Note that $L_{inp} + L_{pun} = L_p$.

2.3. *Consequence Uncertainty*

The consequences due to the burst of a natural gas transmission pipeline can be categorized as,

1. Safety consequences: Ignition of the natural gas release is often modelled to result in a stable jet fire and the expected number of fatalities are estimated based on the thermal

radiation generated due to the jet fire and likelihood of the presence of the receptors. These safety consequences are estimated as expected number of fatalities and are converted to the safety costs using the value of statistical life (VSL). However, the estimated safety costs would be uncertain primarily due to the probability of ignition, probability of presence of the receptors, and the duration of exposure to the thermal radiation.

2. Reputational consequences: Reputational consequences occur if the pipeline burst has been noticed by the public and impacts public convenience even though there are no other safety or operational consequences. The severity of reputational consequence depends on ignition of gas release, duration of jet fire or blow-down, proximity to the population centers and roadways. The monetary impact of these consequences would be through challenges to future access to pipeline right-of-way for repair or monitoring from the land owners, obtaining permits for expansion, and potential sabotage or vandalism. More directly, reputational consequences impact market evaluation of the enterprise stocks and result in loss of share value.
3. Regulatory consequences: Any reportable failure incident attracts additional scrutiny of the regulatory bodies and the monetary impacts of the consequence are the loss of revenue due to imposed pressure restrictions, increased prevention, inspection, monitoring and mitigation activities with prescriptive rules and increased conservatism, increased process auditing of the pipeline integrity management. In longer term, the regulatory consequences would also impact approvals of special permits for deviations from the existing standards and regulations.
4. Business consequences: A pipeline failure incident would have immediate business impact due to loss of product, and inability to meet the delivery requirements. In addition, the commercial impacts may extend to future delivery contracts due to loss of competitiveness and reliability of the delivery. Furthermore, ignited gas releases would also result in property damage, and legal costs.
5. Environmental consequences: For unignited gas releases, the loss of product would result in release of green-house gas (GHG) emissions, and ignited gas release could lead to GHG emissions due to the ignition of the surrounding combustible materials. Although the environmental consequences are not currently monitored for the pipeline failures, as the organizations move towards carbon capture and carbon credits, these events would add environmental costs.

Available data on natural gas pipeline incidents is limited to the safety costs, and property damage, without any public domain data related to the intangible costs of reputation, regulatory and other business costs. For the transmission pipelines in the U.S., Anderson (2020) reports the mean cost of a failure incident as approximately \$1.48 millions with a standard deviation of \$19.6millions. Given that the standard deviation is 10 times the mean, the uncertainty in the consequence costs dominate over all other uncertainties in the estimation of the failure probability and the expected number of failures.

As safety consequences are known to be affected by the population density of the pipeline as well as the thermal radiation of the jet fire, considering these factors in the estimation of the safety costs would reduce the uncertainty. In particular, pipeline diameter and operating pressure affect the probability of ignition and the impact zone of jet fire while the location class can be used as a proxy for population density and the presence of receptors. As literature is available to estimate the population density as a function of location class in North America (Nessim et al 2004), potential impact radius of the jet fire (Stephens et al. 2002) and probability of ignition (Acton and Baldwin 2008), safety costs can be estimated with the most certainty among all the consequences based on the pipeline design and operational factors.

Although property damage is influenced by the impact radius of the jet fire, the incident data summary by Belvederesi and Dann (2017) indicates that the mean and variance of the property damage costs are largely independent of the location class and can vary over four orders of magnitude with the range of \$10,000 to \$10,000,000. The costs due to other business costs and regulator costs can be estimated by the reduction in volume of gas deliveries due to pressure reductions, increased maintenance activities, and direct volume lost during the pipeline failure event. Although statistics for reputational and legal costs are not readily available in the public domain, the legal settlement costs, regulatory fines, and loss of stock value from the San Bruno incident (NTSB 2011) to the operator Pacific Gas and Electric (PG&E) indicate a range of \$500 million to \$2 billion (NYT 2015). Based on these estimates, the total cost of failure has variability from \$10 thousand ($\$10^4$) to over \$1 billion ($\$10^9$), with high likelihood of costs between \$1 million ($\$10^6$) to \$100 million ($\$10^8$).

3. NUMERICAL EXAMPLE

3.1. *Problem Description*

The proposed approach for VoI estimation in this study is demonstrated through application to a hypothetical pipeline with input parameters selected from the literature. The inspection decision is to conduct ILI for external cracking on the pipeline, with estimated cost of \$2 million per pipeline segment of 100km. Figure 1 shows the typical stress corrosion cracking (SCC) as a crack field on the pipeline and typical idealization of the largest crack as a semi-elliptical profile for burst pressure capacity assessment. Table 1 shows the selected pipeline parameters.

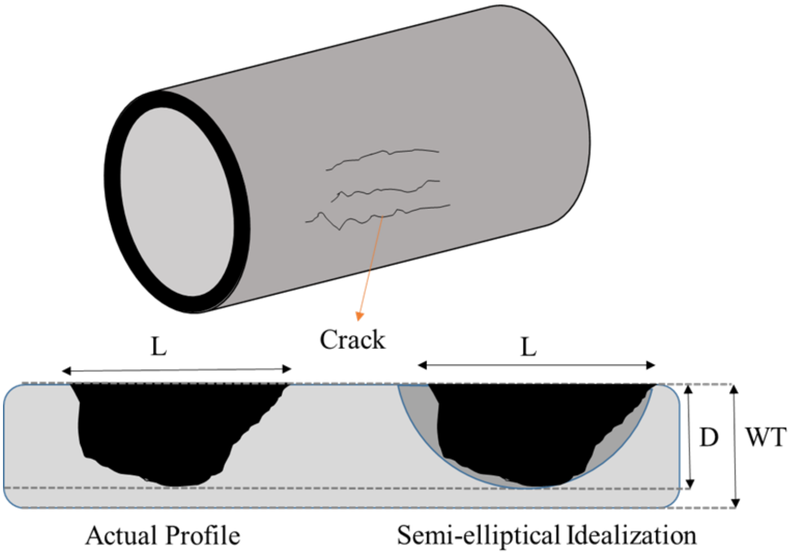

Figure 1 Pipeline defects and idealization

Table 1 Pipeline parameters

Parameter	Value	Units
Outside diameter	508	mm
Wall thickness	6.35	mm
Yield strength	358.53	MPa
Tensile strength	455.05	MPa
Toughness CVN	85	J
Operating pressure	936	psi

To estimate the expected number of failures due to SCC before conducting the ILI, the density of likely cracks is estimated as one per km. The distribution of crack sizes required to estimate the burst pressure capacity in the presence of a potential crack are estimated from a representative pipeline where ILI detected crack sizes are known. Figure 2 shows the data set for crack sizes, which was adopted from the inspection data in Yan et al. (2020).

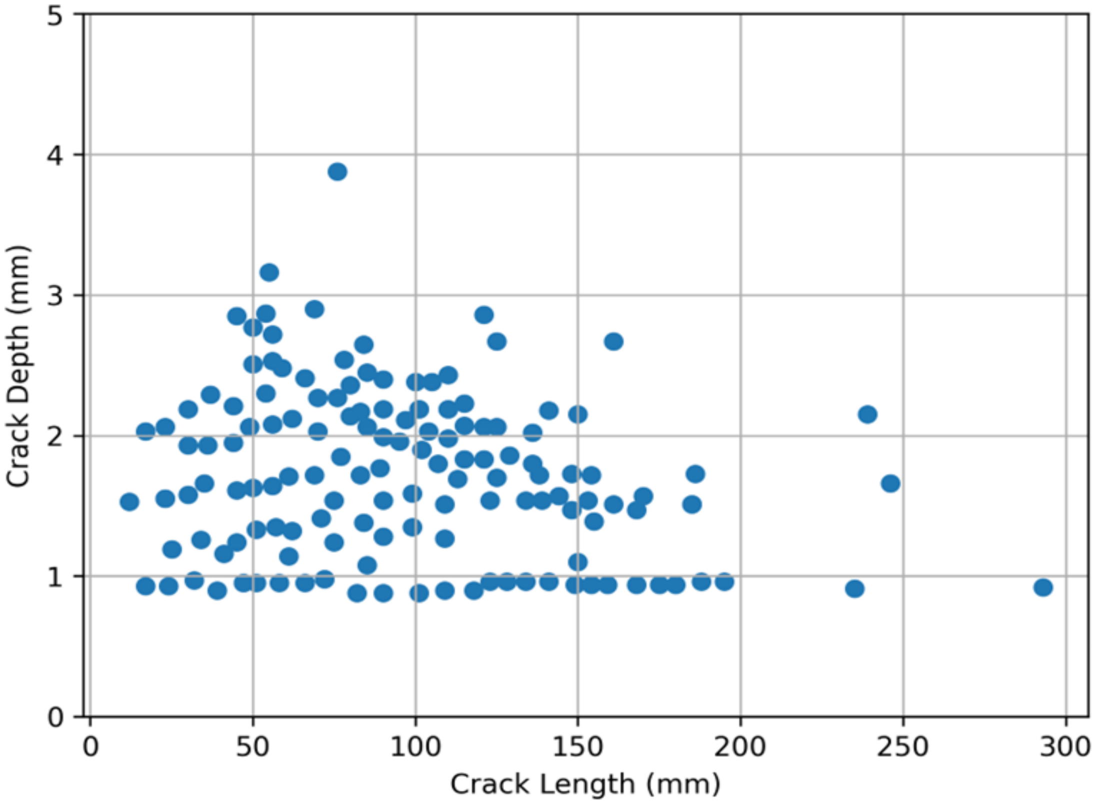

Figure 2 Estimated crack sizes

Table 2 shows the random variable distributions derived for the crack depth and length and estimated correlation coefficient is -0.186. A slight negative correlation is expected as the longer cracks in a crack field are due to coalescence of shallow cracks. Conversely, isolated cracks tend to grow in depth due to stress intensity and as such, deeper cracks tend to be shorter than 200mm. In addition to the aleatory random variables, such as pipe properties and defect geometry, epistemic uncertainty due to model error is also modelled as a random variable. In the present study, CorLAS ® (Jaske and Beavers 2001) model is used to estimate burst pressure capacity of SCC and the model error estimated from Yan et al. (2014).

Table 2 Random variables

Parameter	Distribution Type	Distribution Parameters	Units
Crack depth	Gamma	(μ=1.725, σ=0.593)	mm
Crack length	Gamma	(μ=97.041, σ=51.395)	mm
Wall thickness	Normal	(μ=6.35, σ=0.25)	mm
SMYS	Normal	(μ=394.383, σ=138.034)	MPa
SMTS	Normal	(μ=509.656, σ=178.38)	MPa
CVN	Lognormal	(μ=85, σ=14.630)	J
Model error	Normal	(μ=1.27, σ=0.21)	-

3.2. *Analysis Approach*

The VoI is estimated for a single pipeline segment of 100km as well as two pipeline systems of lengths 1000km and 10,000kms. The probability of failure of any single defect on a pipeline segment P_{fi} ($g\leq 0$) is estimated using Monte Carlo simulation with random variables provided in Table 2, and CorLAS® model for the estimation of the burst pressure capacity. Table 3 shows the input parameters to estimate Eq. (2) and Eq. (4). The tool is to assumed to have perfect detection when the defect size exceeds the depth and length detection thresholds. Therefore, P_{fi} ($g\leq 0|s>S$) is estimated for the combined depth and length thresholds shown in Table 3.

Table 3 VoI inputs

Parameter	Pipeline Segment	System 1	System 2
Length (km)	100	1000	10000
Defect density ρ_i (per km)	1	1	1
Baseline cost of failure (C_f) ($)	10,000,000	10,000,000	10,000,000
Compounding factor for undetected cracks (α)	1.2	1.2	1.2
Compounding factor for detected cracks (α_d)	1.2	1.2	1.2
Average cost of repair ($)	200,000	200,000	200,000
Average cost of inspection ($ per 100km)	1,000,000	1,000,000	1,000,000
ILI tool detection thresholds (depth mm, length mm)	2mm, 50mm	2mm, 50mm	2mm, 50mm
P_{fi} ($g\leq 0$)	0.001522	0.001522	0.001522
P_{fi} ($g\leq 0 \mid s>S$)	0.00308	0.00308	0.00308
P_{fi} ($g\leq 0 \mid s<S$)	0.00108	0.00108	0.00108
p_d	21.96 %	21.96 %	21.96 %
p_{ud}	79.04 %	79.04 %	79.04 %
P_{fa} (per km)	10^{-4}	10^{-4}	10^{-4}

3.3. *Results and Discussion*

Figure 3 shows the VoI estimate for a single Pipeline Segment and System 1 along with the estimated prior and pre-posterior costs. As evident from the figure, the VoI does not exceed the cost of inspection for both the single Pipeline Segment as well as System 1. Due to the low density of crack features and the low probability of failure of any given crack, the expected number of failures do no exceed 1.0 for a smaller system size, and thus not justifying the inspection costs incurred due to sophisticated ILI tools.

In contrast, Figure 4 shows that the VoI is higher than the inspection costs on System 2. This is due to the increase in estimated expected number of failures prior to inspection as the system size increases, and this introduces the effect of compounding factor when expected number of failures are greater than 1.0. In this case, the higher cost of inspection is justified although the total system inspection costs far exceed the inspection of a single Pipeline Segment or System 1.

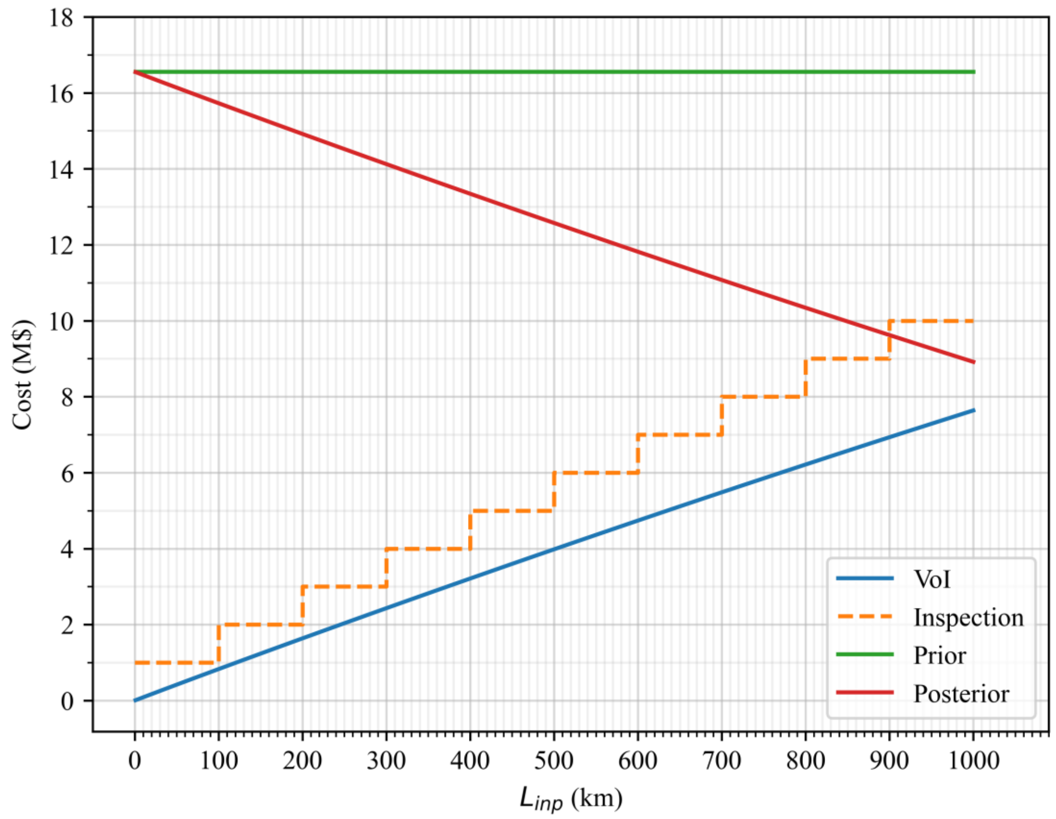

Figure 3. VoI for System 1 (1000 kms)

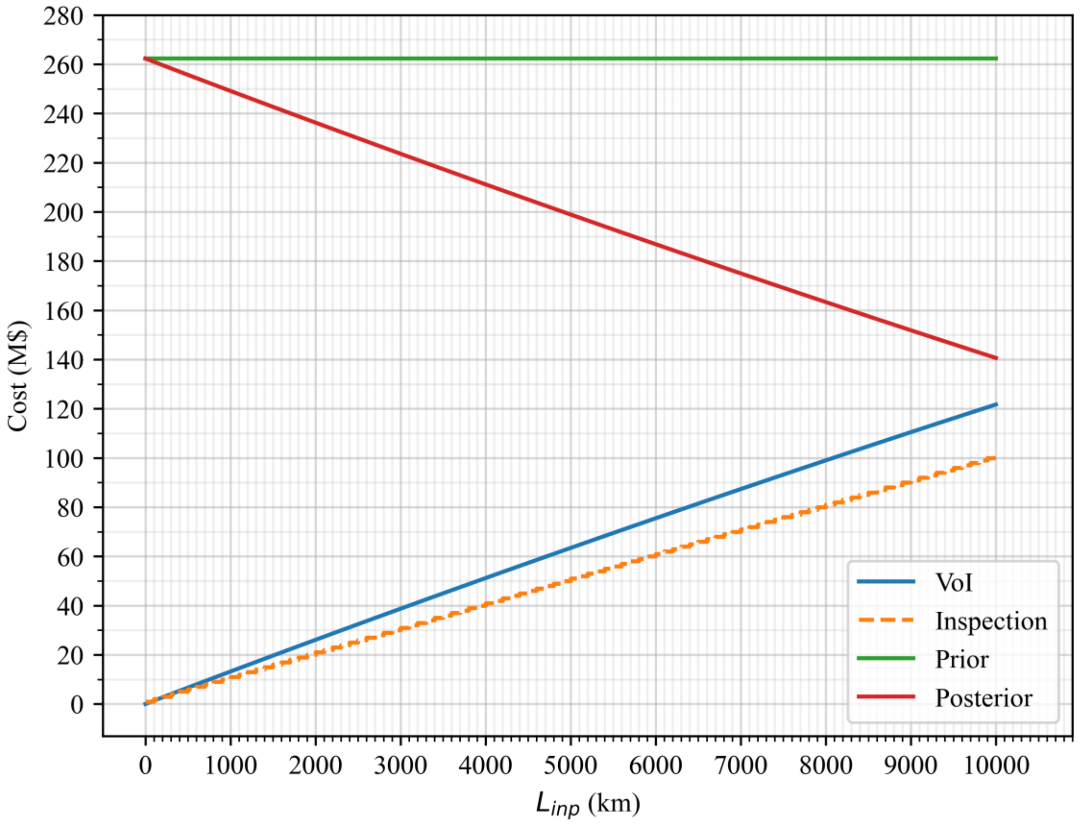

Figure 4. VoI for System 2 (10,000 kms)

If the cost of failure is represented as uncertain, then the decision regarding the VoI and inspection costs may vary based on the confidence the estimated cost of failure. Figure 5 shows the variation in the VoI for a single Pipeline Segment with the varying cost of single failure. In this case, even an increased cost of inspection up to \$2 million is justified, if the cost of failure is \$40 Million. Given high likelihood of costs between \$1 million (\$$10^6$) to \$100 million (\$$10^8$), the variation of the average cost of a single failure from \$10 million to \$40 million would be justified, and thus the decision for inspection is influenced by considering the uncertainty of the failure costs.

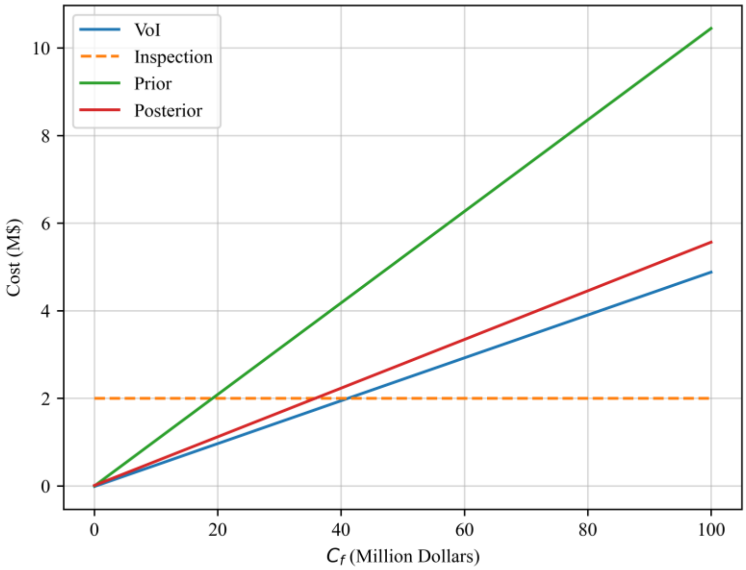

Figure 5. Effect of C_f on different costs and VoI for a 100km Pipeline Segment

By explicitly modelling the probability distribution of the cost of failure, the distribution of the VoI may also be estimated. Figure 6 shows the modelling of the cost of failure due to safety and property damage costs estimated from public domain data source of pipeline incidents maintained by Pipeline and Hazardous Material Safety Administration (PHMSA), under the U.S. Department of Transportation (U.S. Department of Transportation (DOT) n.d.). The costs are modelled as a triangular probability distribution function (PDF) with a minimum value of \$10,000 (\$$10^4$), most likely value of \$10 million (\$$10^7$), and maximum value of \$300 million (\$$3\times10^8$).

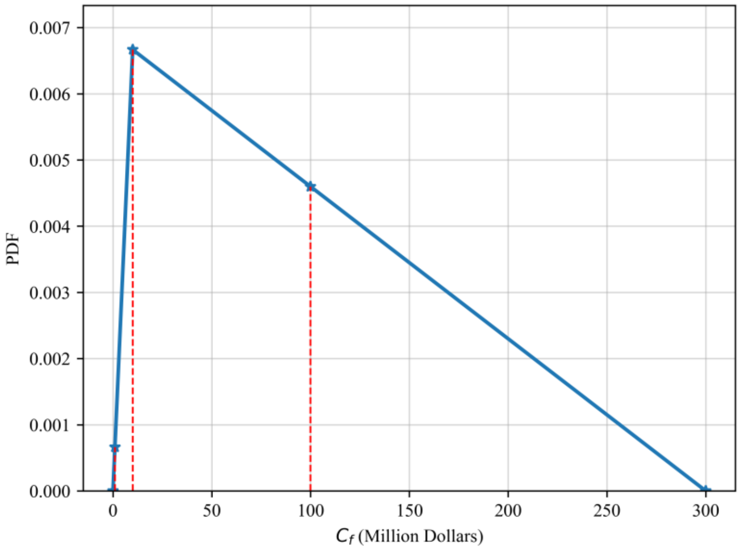

Figure 6. Triangular PDF of C_f based on safety and property damage costs

The VoI increases with the increase in cost of failure due to the direct scaling effect of both prior and pre-posterior costs due to cost of failure. Figure 7 shows the cumulative distribution functions (CDF) for cost of failure shown in Figure 6 and the corresponding VoI estimated for a single Pipeline Segment of 100 km. For the most likely cost of failure of $10 million, the VoI corresponding to 100km is considerably less than $1 million (see Figure 5). From Figure 7, it is seen that the VoI of $1 million corresponds to a probability of 10%. Therefore, there is a 90% probability that the inspection costs greater than $1 million are justified when the uncertainty is included even for the partial costs of failure.

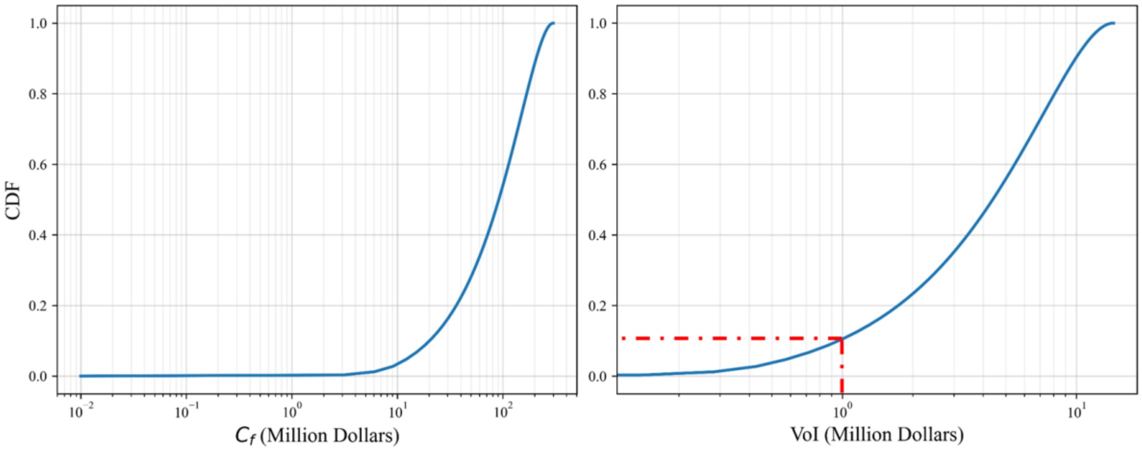

Figure 7. CDF of C_f and VoI for a single100km Pipeline Segment

4. CONCLUSIONS

This paper provides a framework for VoI decision-making for pipeline inspection and integrity management that includes the cumulative effect of costs on multiple failures and the effect of cost of failure uncertainties on the estimated VoI. The framework was applied to a hypothetical pipeline with the representative defect population obtained from the inspection of a similar pipeline. The VoI results indicate that an expensive inspection program is justified on a larger pipeline system – when compared to a smaller system of similar characteristics – to reduce the costs that may occur due to compounding effect of multiple failures. In addition, with consideration of the variability in the cost of failure, the inspection program on a single pipeline segment may also be justified depending on the risk averseness of the decision maker.

The application in this work was limited to the perfect inspection performance of the ILI tools, and the future work focuses on the inclusion of the uncertainties in the ILI tool detection, identification and defect sizing performance, as well as the uncertainties in crack growth mechanisms on the estimated VoI. The sensitivity of the optimized rational decisions under both inspection uncertainties and cost uncertainties are explored in the future research.

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