A Matrix-Based Risk Assessment Approach for Addressing Linear Hazards such as Pipelines

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Abstract:

Pipelines represent a linear risk source that can create unique challenges when assessing risks. In the past, risk has been managed by identifying construction requirements and setbacks based on population densities and types of land use. In the current risk assessment a matrix-based approach has been developed so as to determine the risks associated with high vapour pressure liquids pipelines. The approach involved the development of a matrix representing each 100 m section of the reviewed pipeline along with approximately 30 risk factors that describe that section of the pipeline. Further, a receptor matrix was constructed to account for each hectare of land within 1 km of the reviewed pipeline system. This approach has allowed for the determination of risk as a function of location and separation from the pipeline and in turn has allowed for the determination of those areas where peak risks exist. In addition, this approach has ensured that the linear geometry related to pipeline risks has been accurately modeled. The resulting estimated risks have been evaluated against MIACC risk thresholds (geographic risk based measures) and against proprietary internal standards (societal risk based measures) held by the client. In this way the acceptability of the risk from both the perspective of the potentially impacted community and that of the pipeline operator can be measured. The net result is that the client has a clear picture of the risks associated with its pipeline and is better able to optimize its risk management and pipeline integrity programs.

Introduction:

The MIACC (Major Industrial Accident Council of Canada) document *"Risk Assessment Guidelines for Municipalities and Industries – An Initial Screening Tool"*[1] gives guidance as to reasonable risk thresholds for varying land uses. Further, the screening tool gives guidance as to how to estimate risk levels based on fixed facilities while stating:

> *"Obtaining individual risk contours for a transport corridor is not straightforward. The issue arises though the "per unit length" frequency units that are used in transportation problems."*

A second MIACC document *"Land Use Planning With Respect To Pipelines – A Guideline for Local Authorities, Developers and Pipeline Operators"*[2] also avoids giving an approach as to how to address the issue of risk calculation with respect to linear risk sources such as pipelines. The document does however suggest that consultation should take place between the various parties when new development occurs based on a separation distance of 200 m. The document then goes on to suggest that this consultation distance should be expanded for high vapour pressure liquids or sour gas pipelines. The goal of this consultation process is to help local authorities in establishing appropriate setbacks, which are not too restrictive nor too conservative.

In the absence of clear guidance as to how to estimate pipeline risk organizations such as the Alberta Industrial Heartland Association[3] have developed their own risk assessment approaches. These types of approaches suffer based on limited data and do not readily reflect the operation of the reviewed pipeline systems, as the operating companies are not involved in the assessment process. As a result these types of risk assessments tend to be overly conservative and have the potential to misinform the public regarding the potential risk levels. This potential overstatement of risks can be of particular concern when pipeline risks are compared to risks related to fixed facilities where more straightforward risk assessment approaches exist.

The lack of accessible guidance with respect to conducting pipeline risk assessments creates a situation where it is critical that pipeline operators readily assess their pipeline systems in a clear manner and be in a position to share this information when needed as per the approach suggested within the MIACC guidelines. In this way local governments can be provided with appropriate information for land use planning purposes allowing for informed and balanced decision making.

Risk can be defined as the product of the likelihood of an event and its consequence. Within the current risk assessment a collection of matrices has been defined in order to allow this relatively simple risk calculation to be computed numerous times so as to give a measure of risk at both a system level and across the system. The various matrices have been defined based on geography whereby 100 m lengths or 1 hectare partitions (100 m x 100 m) have been utilized. 100 m was selected as it represented a distance where factors associated with data quality, computational needs, and geometry could be best balanced. At shorter distances data quality and computational needs become an issue. At larger distances errors associated with geometry assumptions can become significant. In addition, assumption as to the uniformity of the risk levels within the measured cell partitions can also become an issue for larger distances.

Through working with and defining the various matrices key information related to the pipeline system can be readily extracted from the risk assessment:

- Failure rate as a function of location (leak and rupture rates were calculated for each 100 m of the pipeline based on 9 different failure modes)
- Distribution of consequences following a release for each hectare of land within 1 km of the point of failure (multiple scenarios were considered and

accounted for day and night conditions, varying wind directions, explosive yields…)
- Geographic risk estimates for each hectare of land within 1 km of the pipeline (this also data was utilized to give risk contours relative to the pipeline)
- Societal risk measures for each hectare of land within 1 km of the pipeline

The net result is that the client can readily view the risk associated with its pipeline systems from a number of perspectives and is positioned to address those areas representing greatest concern. Further, through an iterative process the client can review various risk reduction strategies so as to determine which activities yield the greatest value by balancing costs against the effectiveness of each strategy.

Failure Rate Determination:

As was stated above failure rates were calculated for each 100 m section of the reviewed pipeline with this calculation being based on the following failure models:

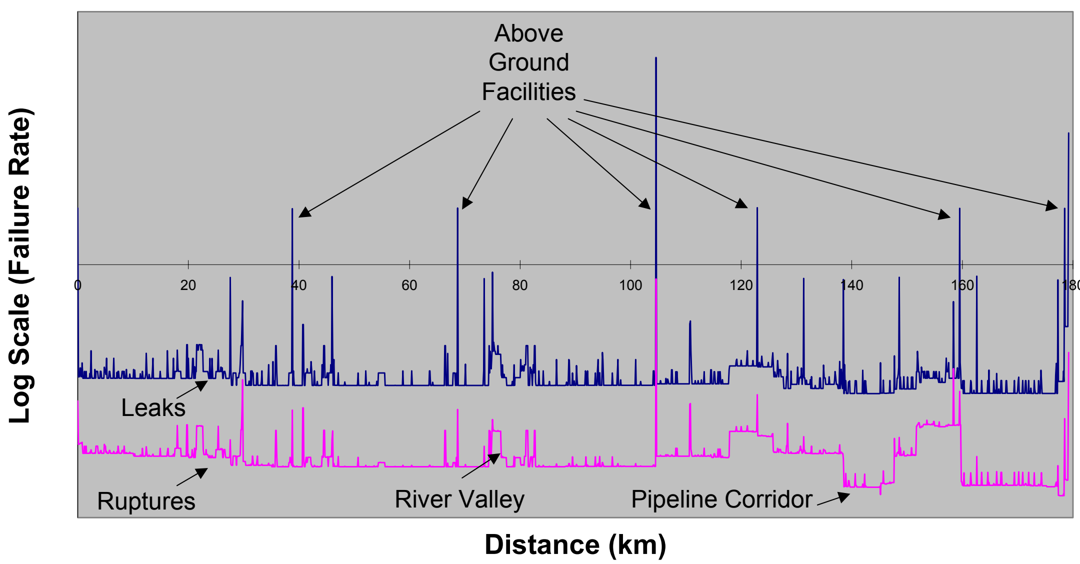
- Internal Corrosion
- External Corrosion
- Stress Corrosion Cracking
- Earth Movement
- Over-Pressure
- Valve/Fitting Failure
- Construction/Material Defect
- Third Party Damage
- Other/Miscellaneous Failures

With the exception of the Stress Corrosion Cracking component the various models were developed based on EUB (Alberta Energy and Utility Board) data[4], which was supplemented by various third party studies and other pipeline incident datasets. The Stress Corrosion Cracking model utilized was based on an internal model held by the client.

As an example of the model development, the external corrosion model started with a base failure rate taken from the EUB dataset with an adjustment factor for pipeline diameter. The failure rate was then adjusted based on coating type utilizing expert judgment and data presented by UKOPA (United Kingdom On-Shore Pipeline Operators' Association)[5]. This base failure rate was then modified in areas where pipe with heavier wall thickness existed. Modifications to the failure rate based on pipe thickness drew upon studies based on data held within the EGIG (European Gas Pipeline Incident Data Group)[6] and the UKOPA[5] incident datasets. Next a series of risk factors were considered and correlations were established between these risk factors (road crossings, creek crossings, power lines, slopes…) and internal inspection data held by the client. These correlations were then built into the failure model so as to allow for the identification of those areas where external corrosion related failures were most likely to occur. The model also accounted for the time elapsed since the last internal inspection was conducted and any anomalies within the current inspection data. The net result was that a model was constructed based on approximately 15 factors that allowed for external corrosion failure rates to be estimated for each 100 m section of the pipeline. Although not directly used the "*Pipeline Risk Management Manual*"[7] served as an excellent reference and aided greatly in the identification of potential risk factors which were considered within the various failure models.

The following graph illustrates the failure rates calculated as a function of location and has been broken out into separate failure rates for leaks and ruptures.

Failure Rate as a Function of Location

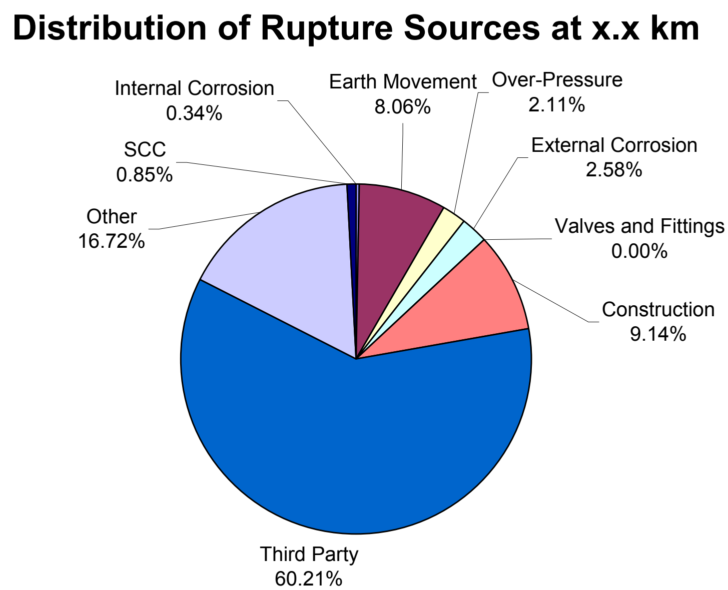


For the pipeline system studied:

- Third party strikes represented the greatest rupture threat
- Rupture rates were typically highest in industrial areas
- Rupture rates were typically lowest within designated transportation utility corridors
- Failure rates typically peaked in valleys where moisture and soil movement concerns existed relative to the surrounding areas
- Developing and existing sub-divisions in areas served by "light wall" pipe represented areas exhibiting higher than average failure rates
- Rupture rates typically varied by a factor of approximately 5 between high failure rate locations and low failure rate locations as observed across the reviewed pipeline system (with the exception of above ground facilities

where failure rates spiked – the observed variation in rupture rates would have been far higher if not for the additional precautions the client currently takes in areas previously deemed to be high risk)

The client was also positioned such that they could readily gain insight into the distribution of failure modes expected for each 100 m section of pipeline. The following graph gives a sample of the breakdown of failure modes expected for a sample urban area. Through understanding the threats that were present for each segment of the pipeline risk mitigation strategies could be readily developed and targeted towards the primary contributors to the expected failure rates.



In general it was found that the estimated failure rates for the reviewed pipeline system were lower than failure rates currently observed for high vapour pressure pipelines within Alberta[8]. This deviation can be readily explained by the high standards to which the client operates its pipeline system along with the larger than average diameter associated with most of this distribution system. (Larger diameter pipelines typically experience fewer failures[4] due to usually better than average maintenance practices and heavier wall thickness.) Further, it was found that the estimated failure rate was readily comparable to that observed for the top performing U.S. hazardous liquid pipeline operators[9]. These comparisons would suggest that at a system level the estimated failure rates are reasonable based on the available data.

Consequence Analysis:

Data held by the U.S. Department of Transportation – Office of Pipeline Safety (U.S. DOT – OPS)[10] related to natural gas liquids pipeline releases were reviewed allowing for a determination of the ignition probabilities and explosion probabilities (delayed ignition) as a function of release size. The resulting ignition probabilities were then modified based on the properties of the potentially released materials relative to the "average" natural gas liquids released and for land use types. For example ignition probabilities should be higher in industrial areas than in open farmland due to the densities of ignition sources associated with these land uses.

Through combining failure rates with the above derived ignition probabilities, as a function of location, it was then possible to estimate the likelihood of the following potentially hazardous events for each 100 m section of the pipeline:

- Small leak (with or without fire and explosion)
- Large leak without ignition
- Large leak leading to fire
- Large leak leading to explosion and fire
- Rupture without ignition
- Rupture leading to fire
- Rupture leading to explosion and fire

Event trees were then constructed for each of the above scenarios based on the following elements (where applicable):

- Time of day (day, night)
- Ignition (immediate ignition, early ignition, late ignition)
- Yield (3% TNT equivalence, 10% TNT equivalence)

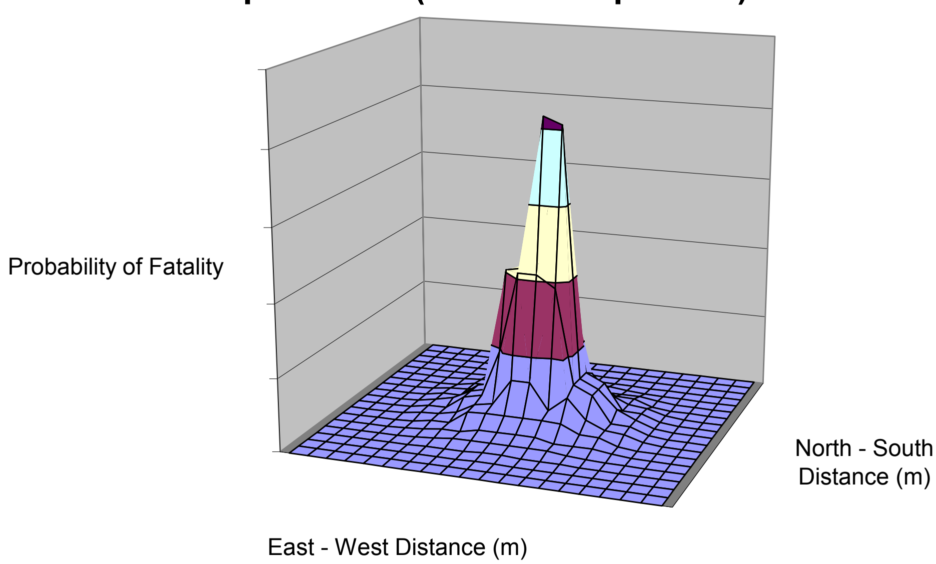
For events leading to fire only the U.S. DOT – OPS dataset[10] was utilized to determine injury and fatality probabilities for individuals residing in the two hectares of land immediately adjacent to the release site (one to the left of the pipeline and one to the right of the pipeline). For fire and explosion events PHAST modeling was utilized to determine occupant vulnerability for each hectare of land within a 2 km matrix surrounding the potential release site. (PHAST is a dispersion modeling and consequence analysis software package that is available through DNV.) It was then possible to develop a matrix that described average occupant vulnerability for each hectare of land within a 2 km square matrix surrounding a release site for each of the identified scenarios through combining the probabilities associated with the different branches of each event tree.

Data generated by the use of the PHAST software was converted from a Cartesian description to a polar notation based description. This transformation allowed vulnerabilities to be readily calculated as a function of distance from the release site. Occupant vulnerabilities were based on values given within the CCPS *"Guidelines for Evaluating Process Plant Buildings for External Explosions and Fires"*[11] and an assumption that those individuals within the lower flammable limit of the resulting vapour cloud would be killed.

In this particular risk assessment the reviewed pipeline runs primarily in a north south direction. This consistent orientation of the pipeline allowed for assumptions to be made as per the direction of the prevailing winds. As such occupant vulnerabilities for each hectare of land were adjusted based on the orientation between the receptor sites and the release site to reflect prevailing wind conditions. This wind adjustment was particularly important in the case of one of the neighboring communities where the typical prevailing wind conditions would suggest that existing housing to the east of the pipeline would be at an elevated risk level relative to the average value calculated for this area.

The following graph illustrates the relationship between occupant vulnerability and location relative to the modeled point of pipeline failure in the event of a rupture and explosion scenario. The graph represents an average outcome accounting for elements such as time of day, wind direction, explosive yield…

Fatality Probability as Function of Location Relative to the Rupture Site (Fire and Explosion)



One of the keys to the current risk assessment approach is that the length scale associated with major events (several 100 m) is significantly larger than the length scale associated with the receptor matrix (100 m x 100 m units). Increasing the resolution of the receptor matrix and working with 1/9th of a hectare units (same total land area covered) resulted in the average occupant vulnerability increasing by less than 1% for those events which resulted in the most significant outcomes (late ignition - rupture scenarios leading to fire and explosion). As such the selected receptor matrix is likely appropriately scaled and represents a balance between resolution and source data quality while ensuring calculation requirements are manageable. In many ways this situation is analogous to the manual integration of the area under a curve – at what point do you have sufficient accuracy to address the question being considered?

Geographic Risk

One common treatment utilized in conjunction with the MIACC methodology is to estimate pipeline risk as per the methodology given for a fixed facility. The resulting distances to the various risk contours estimated in this manner are then applied perpendicular to the pipeline to create risk corridors aligned with the pipeline. Typically people equate the MIACC failure rates with 1 km of pipeline and as such this approach results in situations where the distance to the risk contours is significantly less than the 1 km length term associated with the estimated pipeline failure rate. The net result is that this approach can significantly overestimate the size of the estimated risk corridor. As an example a fixed facility that is found to represent a certain risk out to 100 m would place an area of 31,400 m^2 at risk, the application of this same distance perpendicular to 1 km of pipeline would place an area of 200,000 m^2 at risk (not including boundary areas). This would indicate that the area at risk had increased by a factor of 6, which represents a significant overstatement, as the energy involved in the source event has not changed.

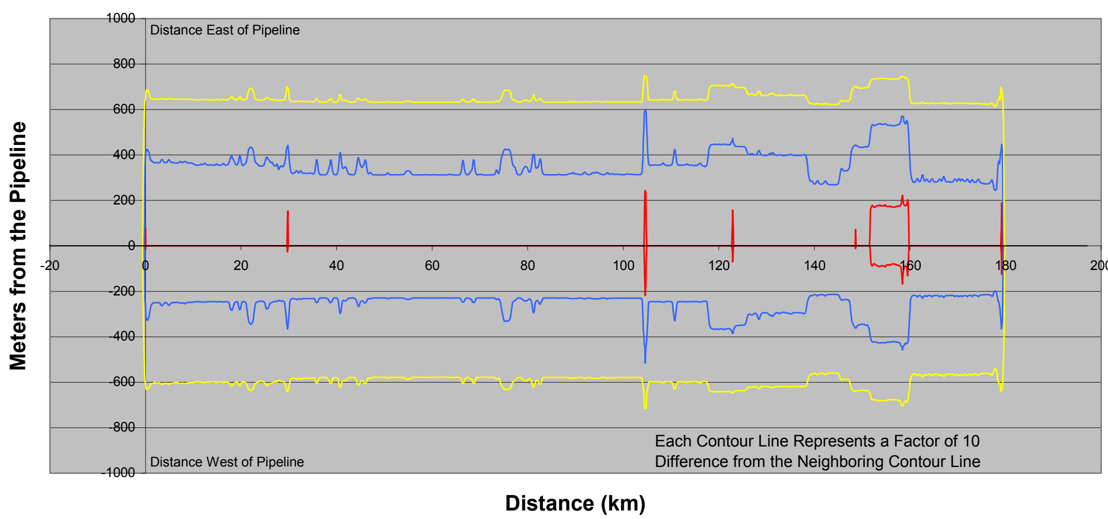
In the current risk assessment the pipeline has been treated as a series of individual risk sources spaced 100 m apart. When reviewing vulnerabilities at a distance of 50 m from the pipeline the calculated risk is approximately 1% below that which would be measured if the pipeline were treated as a series of individual risk sources spaced 33.3 m apart. This would suggest that the resolution granted by the receptor and consequence matrices is appropriate as per the balance between computational needs and the accuracy of generated results.

Essentially the geographic risk for a given hectare of land can be determined by considering each 100 m section of the 2 km of pipeline closest to the location being analyzed. When reviewing each 100 m section of the pipeline the impact of the modeled consequences for each of the reviewed scenarios is considered based on the separation between each 100 m section of the pipeline and the hectare of land being reviewed. In this way the various risks associated with each hectare of land within 1 km of the pipeline can be readily estimated. Clearly the use of tools such as spreadsheets can greatly facilitate this analysis. In the current assessment over 45,000 hectares of land were considered based on 7 outcome modes (with some outcome modes representing averages accounting for multiple event severities) being applied to just over 2,300 sections of pipeline.

This approach resulted in the ability to classify each hectare of land as per the MIACC land use guidelines. Further, by extrapolating between the values obtained for the midpoint of each hectare of land it was possible to generate approximate geographic risk contours. The term approximate has been used as a linear fit was used between data points rather than a more robust curve fit. Further, the approach did not account for the fact that peak risk levels were typically found between 50 m and 150 m on the downwind side of the prevailing winds. As such the risk contours do not exhibit the same level of accuracy as the other values put forward within this approach. More involved curve fitting could be conducted so as to improve the accuracy of the analysis but was not deemed to be necessary within the current study as a hectare based level of resolution was deemed to be acceptable. Although not fully analyzed, peak risk levels were typically found to be 10%-15% above the levels found at 50 m downwind and 150 m downwind of the pipeline and as such the geographic risk contour may not capture these peak values as a result of the hectare based resolution used within this calculation (50 m downwind and 150 m downwind were found to yield similar risk values indicating peak risk levels occurred between these two points). It should also be noted that the MIACC risk thresholds are based on a log scale and as such the introduced error factor in this particular calculation is not as significant as it appears at first glance.

The following graph illustrates the geographic risk contours estimated through this risk assessment for the client's pipeline system.

Individual Fatality Risk Contours



The estimated geographic risk values, in combination with current land uses, indicated that the operation of the pipeline system is well within the MIACC guidelines. i.e. from a community perspective the operation of the reviewed pipeline, as per the current integrity program, does not represent a significant hazard.

Modeled Outcomes

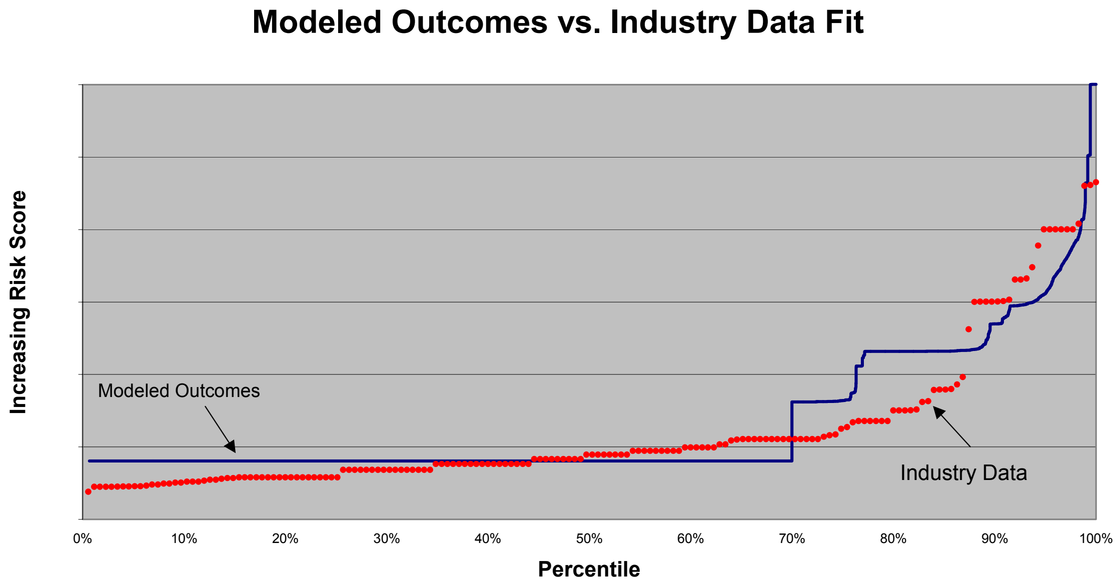
The MIACC guidelines strive to measure risk acceptability from the perspective of the potentially impacted communities. However, this risk measure does not indicate if an activity is acceptable from the perspective of the operating company. Both of these perspectives need to be reviewed in order for a risk assessment to be considered complete. In this particular case the client utilized a risk scoring methodology that assigns values to various events across several categories when judging risk. The following categories were considered within in this methodology:

- Fatality/Injury/Illness
- Exposure
- Quality of Life
- Financial Impacts
- Environment
- Regulatory

These event values are combined with probabilities of occurrence and summed to give risk scores, which are then judged against risk thresholds to determine the client's acceptability of the risks associated with a given activity. Consequence models were built for each of the categories based on data within the receptor and pipeline characterization matrices. Through combining the event probabilities with the consequence models and the receptor matrix it was possible to determine a risk score for each 100 m of the reviewed pipeline using the client's value system.

In this particular case the resulting risk scores were dominated by the potential for fatalities, particularly as related to rupture events leading to fire and explosion. Within the client's methodology scores assessed for fatalities were non linear such that multiple fatality events received far greater scores than those obtained for individual fatality events. i.e. if 1 fatality had a value of X an event leading to 2 fatalities would have a score of 4X. Generally the scores within the client's methodology scaled with the square of the number of fatalities resulting from a given event. (Although not conducted within this particular study the determination of the number of fatalities per event along with the associated event frequencies gave sufficient details to judge risks based on the application of F-N curves. This analysis has been conducted as part of a subsequent pipeline risk assessment looking at a different pipeline system.)

In order to validate the range of events that were being simulated within this analysis the clients risk scoring methodology was used to score the natural gas liquids pipeline failure data contained within the U.S. DOT – OPS dataset[10]. The following graph illustrates the risk scores that were assigned to the 170 plus incidents within the U.S. DOT – OPS dataset[10] and the risk scores obtained for the entire range of modeled outcomes within the current study using the client's value system. On a percentile basis it is clear that the two datasets track in a consistent manner. This would indicate that the modeled outcomes are of an appropriate and reasonable severity based on the range of events that have been observed.



Deviations in the 70^{th} thru 85^{th} percentiles primarily relate to financial factors as the U.S. data included limited information with regards to the total financial losses associated with each event.

Societal Risk

Societal risk based measures, viewed from the perspective of a corporation, attempt to gauge the impact the surrounding community will have on the corporation as a result of the potential impact the corporation has on the community. The non-linear relationship between fatality number and risk value reflects the greater outrage a community will express as related to multiple fatality events compared to individual fatality events. This greater outrage has the potential for greater regulatory intervention and financial costs, which in turn increases the likelihood that the event will threaten the survivability of the organization. The difficulty with pipelines when assessing societal risk is that a pipeline has the potential to cross through multiple communities. This leads to the question as to what is an appropriate distance of pipeline to consider when assessing risk to a corporation based on risk to a community. If you consider 10 km of pipeline verses 100 m of pipeline the risk found for a 10 km of section would typically be 100 times larger than that measured for a 100 m section. The net result is that the length of pipeline considered is a key parameter when reviewing societal based risks – terms related to outcomes do not change significantly with length but the failure rate, which is expressed as a function of pipeline length, obviously does vary.

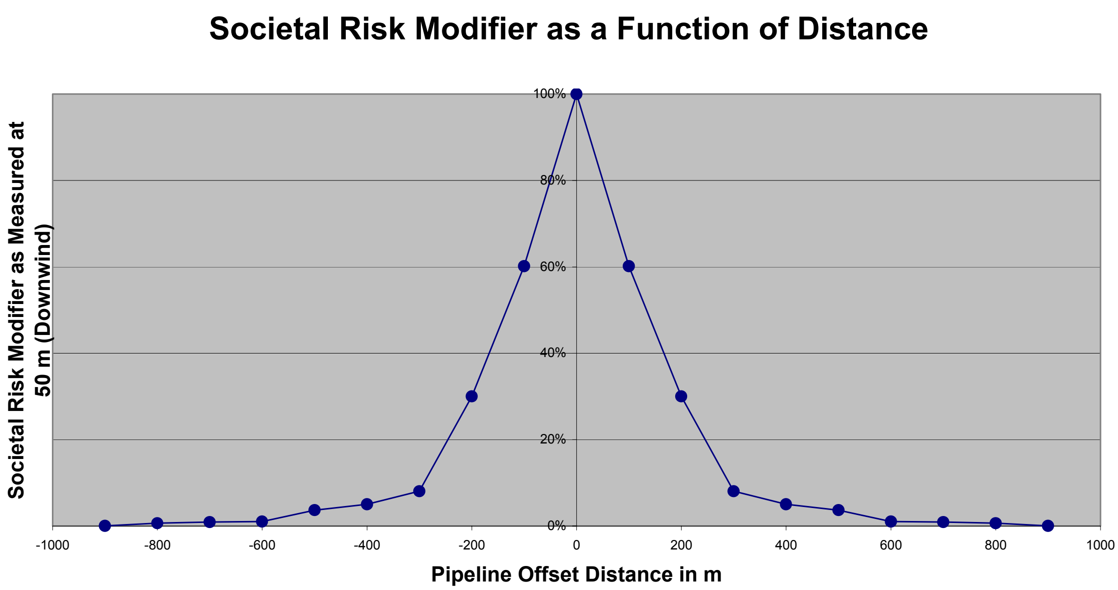
One potential approach is to look at worst-case scenarios and then consider a section of pipe consistent with that length value. This approach however suffers from two main issues. First worst-case scenarios often can be extremely difficult to define and second at what distance from an event does one consider the impact to be zero. As a result the distance considered for a worst-case scenario can vary dramatically from one study to the next. If one considers incidents like Port Hudson[12], where windows were damaged for several kilometers, the distances associated with worst-case scenarios can be quite large while the frequency of this type of drastic event is extremely low. Further, even if this large worst-case type of event did occur this type of event tends to be directionally focused indicating that someone could be present within this worst-case distance from the release site while still having a low probability of being affected. Although reasonable these approaches can be extremely conservative in nature when compared to similar calculations addressing fixed facilities and can be difficult to define.

Ultimately the goal is to develop an approach that allows for comparisons to other risks managed by the client to be made. In this case the client is primarily involved in the petrochemical industry and as such has a strong bias towards fixed facilities. The net result was that it was key that the approach generated risk values which could readily be compared to fixed facilities. It is important to note that the perspective being considered is from that of the company involved and as such the company has the ultimate say in determining what is acceptable and how the risk is to be both defined and judged. In the long term those standards and methodologies will determine the success and viability of the company in question.

In this case the approach taken has been the determination of a peak societal risk value for each 100 m of the pipeline. This peak societal risk has been calculated based on the societal risk estimated for the hectare of land immediately to the east of the pipeline where prevailing wind conditions result in peak geographical risk. The calculation involved looking at all events which could impact that hectare of land and determining risk scores, using the client's methodology, and frequencies for each event along with the probability that the events would actually impact the particular hectare of land being considered. As such, events occurring in the immediately neighboring 100 m section of pipeline were counted at full value while more distant events were scaled to reflect the declining probability that the event would have an impact within the hectare of land being considered. The probability that a neighboring event would impact the considered hectare of land has been termed the societal risk modifier within this study. The societal risk modifiers could be readily calculated thru modification of the occupant vulnerability matrix developed using the PHAST analysis. Essentially the probability of impact was defined in place of the probability of fatality or injury used in the consequence portion of the risk assessment. The benefit to this approach is that the contribution of more distant events is reduced and as a result extremely low probability worst-case scenarios do not tend to skew the analysis.

Increasing the resolution of the receptor matrix by changing the size of the partitions from 1 hectare cells to 1/9th of a hectare cells resulted in the estimated societal risk modifier values decreasing by approximately 3% for rupture and explosion events when summed over the neighboring 2 km of pipeline (1 km was found to represent a distance at which the societal risk modifiers goes to zero). As such the use of 1 hectare sized cells, as used elsewhere within this analysis, represents a reasonable balance between accuracy and computational requirements.

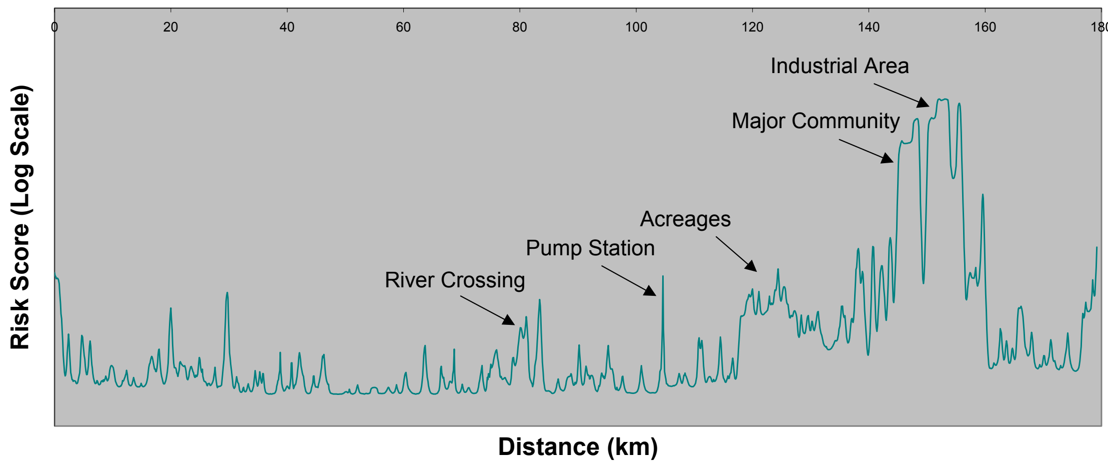
For the particular material being shipped by this pipeline system the equivalent pipeline risk distance term was found to be approximately 320 m. i.e. under uniform conditions the societal risk as measured by this methodology equates to a societal risk equivalent to that measured for a 320 m section of pipeline. The equivalent pipeline risk distance term can be determined from the area under the curve within the following plot illustrating the societal risk modifiers as a function of distance from the hectare of land being considered.



The above graph illustrates the societal risk modifiers developed for the hectares of land immediately to the east of the pipeline (downwind side) for each 100 m segment of pipeline within a kilometer of the hectare of land being considered. As an example, if a rupture and explosion were to occur 400 m north of the hectare of land being considered there would be approximately an 8% probability that the hectare of land being considered would be impacted by the event. As such the societal risk score calculated for this failed segment of pipeline would be scaled by the 8% value when determining the contribution of this event to the total societal risk score for the hectare of land being considered located 400 m away. The graph also shows how the impact to the measured societal risk score goes to zero for scenarios occurring more than a kilometer away from the point being reviewed.

The following graph illustrates the societal risk values measured within this study as a function of pipeline location.

Societal Risk Score as Measured as a Function of Location



Ultimately this approach generated risk values that the client could readily compare to previously conducted risk assessments for various fixed facilities. This in turn enabled the client to view the measured pipeline risks within the context of the portfolio of risks the client is actively managing.

Conclusions:

Due to the linear nature of pipelines most risk assessment techniques fail to generate risk values that can be readily compared to fixed facilities. This difficulty in analysis combined with limited agreement on how best to conduct these types of assessments has resulted in a situation where various levels of government are being hampered with respect to land use planning. As a result it is critical that companies involved in pipeline operations conduct their own risk assessments and be in a position to share their findings with appropriate levels of government if asked.

The current risk assessment utilized a matrix-based approach whereby the linear nature of pipeline systems was approximated by a series of fixed risk sources. The nature of the matrix was such that separation between the approximated risk sources was sufficiently smaller than the estimated impact distances for major rupture events leading to fire and explosion. As a result the errors introduced by this approach relative to a linear system were minor and well within the accuracy of the assessment. Comparisons between the estimated failure rates and consequences obtained within this study relative to observed outcomes, primarily U.S. experience, indicate that the current risk assessment is reasonable and accurately reflects the reality of the analyzed system. This approach yielded both geographic risk levels, which allowed for comparisons against external risk guidance given in the MIACC guidelines, as well as a measure of societal risk, which allowed for comparisons against risk thresholds held by the client. Further, the societal risks were calculated in such a manner that they could be readily related to other risk assessments conducted by the client related to fixed facilities. In addition to addressing risk related concerns the assessment also yielded data related to failure rates and clearly positioned the client such that risk mitigation measures and pipeline integrity programs could be readily optimized.

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