PROBABILITY OF IGNITION MODEL FOR RUPTURE OF ONSHORE GAS TRANSMISSION PIPELINE AND ITS APPLICATION IN PIPELINE RISK ASSESSMENT

Chio Lam, M.E.Sc. Candidate, Dept. of Civil and Environmental Engineering, University of Western Ontario, London, Ontario, Canada
Wenxing Zhou, Assistant Professor, Dept. of Civil and Environmental Engineering, University of Western Ontario, London, Ontario, Canada

Abstract: An ignited rupture of a gas transmission pipeline has serious consequences in terms of human safety. The evaluation of the probability of ignition (POI) for a potential pipeline rupture is therefore critical for the risk assessment of pipelines. This paper proposes a log-logistic regression model to evaluate the probability of ignition for ruptures of onshore gas transmission pipelines. The pipeline incident data collected by the Pipeline and Hazardous Material Safety Administration (PHMSA) of the United States Department of Transportation (DOT) are utilized to develop the POI model, as a function of the pipe diameter and operating pressure. The parameters in the model are estimated using the maximum likelihood method. The proposed probability of ignition model is applied in the quantitative risk assessment of a hypothetical gas pipeline. The societal risk level associated with the hypothetical pipeline is quantified by considering the probability of rupture, probability of ignition given rupture, and population distributions in the vicinity of the pipeline. The proposed POI model will facilitate the risk assessment of onshore gas transmission pipelines.

1 Introduction

Pipeline is considered to be the safest way of transporting high quantity of natural gas through a long distance. Failures of pipelines do happen, although infrequently. Among all failure modes, ignited ruptures of gas pipelines have the most severe consequences in terms of human safety and property damage. Therefore, it is important to develop a probability of ignition model for ruptures of gas pipelines to facilitate the pipeline risk assessment.

Several linear regression POI models for ruptures of gas transmission pipelines derived using the PIPESAFE Group data from 1970 to 1996, those from 1970 to 2004 and the U.S. PHMSA data from 2002 to 2007, were published in 2008 (Acton & Baldwin 2008). However, there are several shortcomings about the linear regression models. First, all the models were fitted by grouping the incident data, giving rise to the concern of the sensitivity of grouping criterion. Second, the models do not necessarily bound the predicted probability within the range from zero to one and require choosing an upper limit for the prediction empirically. The last but not the least, the underlying assumption of using the least-squares method to fit the linear regression models is violated since the binary responses (e.g. 0 and 1 for not ignited and ignited, respectively) in the data do not have constant variance and do not vary about the mean according to a normal distribution (Stephenson et al. 2008). Therefore, an improved POI model needs to be developed. As most gas pipelines in the U.S. and Canada are onshore transmission pipelines, this study focuses on developing the POI model for ruptures of onshore gas transmission pipelines.

For binary data, the logistic regression analysis has been recommended in the literature as an appropriate way to model the response (Stephenson et al. 2008, Rodriguez 2007). In this study, a log-logistic regression model was proposed as the POI model. The model parameters were evaluated using the maximum likelihood method based on the PHMSA pipeline incident data between 2002 and 2014. The proposed POI model is then applied in the quantitative risk assessment of a hypothetical gas pipeline.

2 Probability of ignition model

2.1 PHMSA data

The PHMSA incident data consist of much information, such as the attributes of failed pipelines (i.e. diameter, operating pressure at the incident time, etc.), failure consequences (i.e. no ignition, ignition only and ignition followed by explosion), failure causes (i.e. corrosion, third party excavation, etc.), and failure modes (i.e. leak, rupture, etc.) and so on. For the analysis of this study, a total of 188 rupture incidents of onshore gas transmission pipelines included in the PHMSA database were selected to carry out the POI model analysis. A summary of the selected dataset is given in Table 1.

Table 1: Summary of the selected datasets from the PHMSA data

p Range (MPa)	p Mean (MPa)	d Range (mm)	d Mean (mm)	No. of ruptures	No. of ignited ruptures
0.3-14.6	4.9	13.7-914.4	438.7	188	57

2.2 Log-logistic regression model

The log-logistic POI model is expressed as follows:

[1a] $\mathrm{Y} = \alpha + \beta \ln(\mathrm{pd}^2)$
[1b] $\mathrm{Y} = \mathrm{logit}(\mathrm{POI}) = \ln \frac{\mathrm{POI}}{1-\mathrm{POI}}$

where α and β are unknown parameters, p is the operating pressure at the incident time, d is pipeline diameter and pd^2 is representing the initial gas outflow following a pipeline rupture. The logarithm of the pd^2 value is taken so that the POI is approximately equal to zero when the pd^2 value is close to zero.
The unknown parameters in the log-logistic regression model are estimated using the maximum likelihood method. Suppose that $\lambda_i = 1$ represents there is ignition in the i^{th} pipeline incident, and $\lambda_i = 0$ represents there is no ignition in the incident. With n independent observations, the likelihood function of the data is as follows:

[2a] $\mathrm{L}(\boldsymbol{\theta}|\mathrm{Data}) = \prod_{i=1}^{n}(\mathrm{POI}_i)^{\lambda_i} \cdot (1 - \mathrm{POI}_i)^{1-\lambda_i}$
[2b] $\mathrm{POI}_i = \frac{e^{\alpha+\beta\ln(p_i d_i^2)}}{1+e^{\alpha+\beta\ln(p_i d_i^2)}}$

where $\boldsymbol{\theta} = (\alpha, \beta)$ is the vector of unknown parameters.
The result of the estimation of parameters in the log-logistic regression model using the maximum likelihood method is shown in Table 2.

Table 2: Estimates of parameters in the log-logistic POI model

Parameter	Estimate	Std. Error
α	-15.36	2.73
β	1.06	0.20

The final log-logistic regression POI model is expressed as the following equations.

[3a] $\mathrm{Y} = -15.36 + 1.06 \ln(\mathrm{pd}^2)$
[3b] $\mathrm{Y} = \mathrm{logit}(\mathrm{POI}) = \ln \frac{\mathrm{POI}}{1-\mathrm{POI}}$

where p in MPa and d in mm.

To estimate the confidence of predicted POI using the above model, the 95% confidence interval of the predicted POI is constructed and plotted together with the empirically evaluated POI values based on the PHMSA dataset, as shown in Fig. 1.

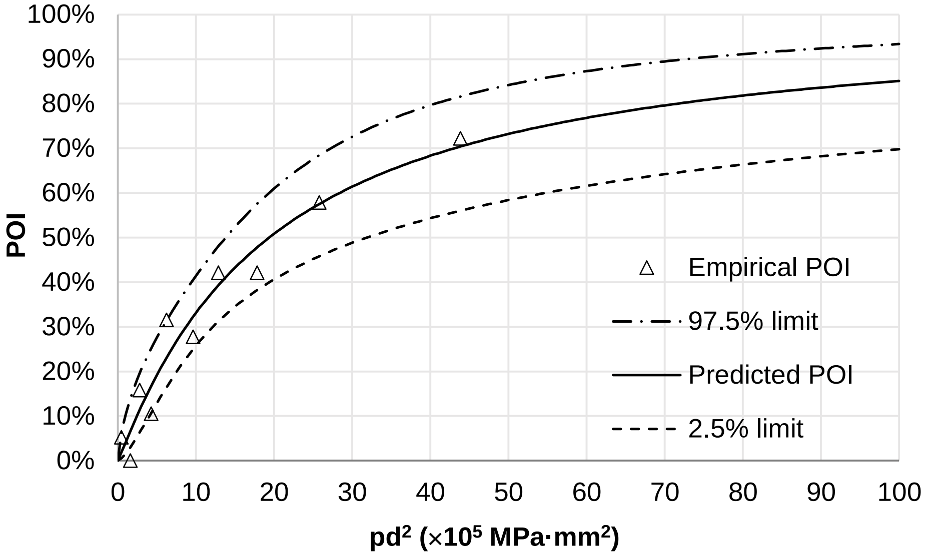

Figure 1: Predicted POI with 95% confidence interval versus pd^2

It is observed that almost all empirical POI data points are within the 95% confidence interval of the predicted POI, indicating that the fitted log-logistic regression model has very good prediction ability, and basically all empirical data points are below the 97.5% limit of predicted POI such that the 97.5% limit can be used as a conservative estimation of the POI for ruptures of onshore gas transmission pipelines.

3 Application in pipeline risk assessment

3.1 Societal risk level

To estimate the societal risk level in terms of human safety imposed by a gas pipeline due to potential incidents of ignited ruptures, the rupture rate of a pipeline and the POI given a rupture need to be evaluated. The societal risk level for location x in the pipeline can be calculated as follows:

[4] $\mathrm{R_s(x) = FR_r \cdot POI_r \cdot C_{ir}(x)}$

where $\mathrm{FR_r}$ is the rupture rate of a pipeline (per km-year); $\mathrm{POI_r}$ is the probability of ignition given a rupture; $\mathrm{C_{ir}(x)}$ is the thermal radiation effect to the surrounding population (i.e. number of casualties caused in the vicinity) due to an ignited rupture in pipeline location x.

In the above, the rupture rate of a pipeline with certain attributes can be obtained through the statistical analysis of PHMSA data; the probability of ignition given a rupture can be calculated using the new log-logistic POI model, and the number of causalities caused in the vicinity given an ignited rupture can be estimated using the following thermal radiation effect model.

3.2 Thermal radiation effect model

The well-known C-FER model (Stephens 2002) is adopted to evaluate the thermal radiation hazard zone associated with an ignited pipeline rupture. The C-FER model assumes a double-ended gas release for a pipeline rupture with the diameter of the release hole at each end equal to the pipe diameter. The radius of a hazard area can be calculated using in the following equation (Stephens 2002, Zhou & Nessim 2011).

[5] $r_{hr} = \sqrt{\frac{0.1547pd^2}{I_{th}}}$

where r_{hr} is the radius of the thermal radiation hazard zone (m), and I_{th} is the thermal radiation intensity threshold (kW/m^2). The radius of the hazard zone due to an ignited rupture can be determined if the pipeline operating pressure, the pipe diameter and the thermal radiation intensity threshold are known.
An ignited pipeline rupture emits thermal radiation to the immediate vicinity of the failed pipeline, the chance of burn injury or fatality of an individual and the probability of ignition of a wooden structure are related to the thermal load received, which is a function of the exposure time and the thermal radiation intensity (Lees 1996). To determine the thermal radiation intensity thresholds corresponding to different levels of casualty for constructing the thermal radiation effect model, a 30-second exposure time is considered a reasonable assumption for an outdoor person to find a sheltered location, considering typical reaction time (1 to 5 seconds) to evaluate the situation in their original position and escape speed of an individual (2.5 m/s) in the direction of shelter and likelihood of finding a shelter within a distance about 60m (Stephens 2002, Rothwell & Stephens 2006, Zhou & Nessim 2011). Given this, the threshold values of thermal radiation intensity corresponding to burn injury, 0% fatality and 100% fatality for people under outdoor exposure are chosen to be 5.05, 12.62 and 31.55 kW/m^2, respectively (Eisenberg et al. 1975, Hymes 1983, Bilo & Kinsman 1997). The linear interpolation method is performed to estimate the intermediate values of fatality probability. A summary of the selected thermal radiation thresholds and corresponding human safety implications for outdoor exposure is depicted in Fig. 2.

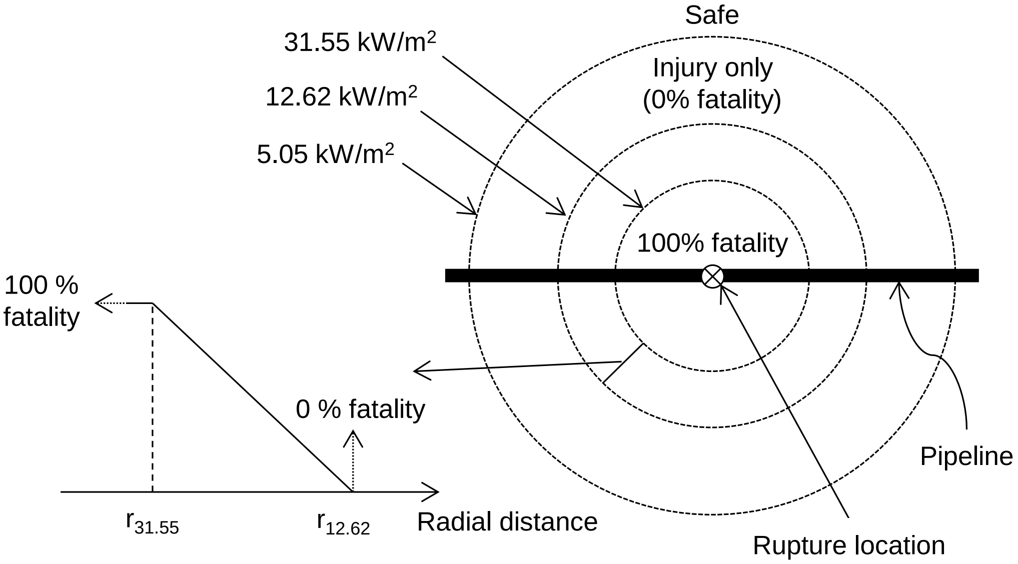

Figure 2: Thermal radiation intensity thresholds and human safety implications for outdoor exposure

For the indoor exposure, wooden structures are unlikely to ignite with a thermal radiation intensity lower than 15.77 kW/m^2, and hence should afford indefinite protection to occupants (Bilo & Kinsman 1997, Stephens 2002). For a thermal radiation intensity greater than 31.55 kW/m^2, such structures will always ignite and provide no protection after ignition. The threshold values of thermal radiation intensity corresponding to 0% ignition probability and 100% ignition probability of a wooden structure are therefore chosen to be 15.77 and 31.55 kW/m^2, respectively. The linear interpolation method is performed to obtain the intermediate values of ignition probability. Given ignition of wooden structures, the threshold level corresponding to 100% ignition probability is assumed to be that of 100% fatality probability for indoor exposure, and the threshold level corresponding to 0% ignition probability is assumed to be that of 0% fatality probability. The intermediate values of fatality probability given ignition of structures are obtained using the linear interpolation method. It is also assumed that the chance of people subject to injury is 100% given ignition of structures. A summary of the selected thermal radiation intensity thresholds and human safety implications for indoor exposure is depicted in Fig. 3.

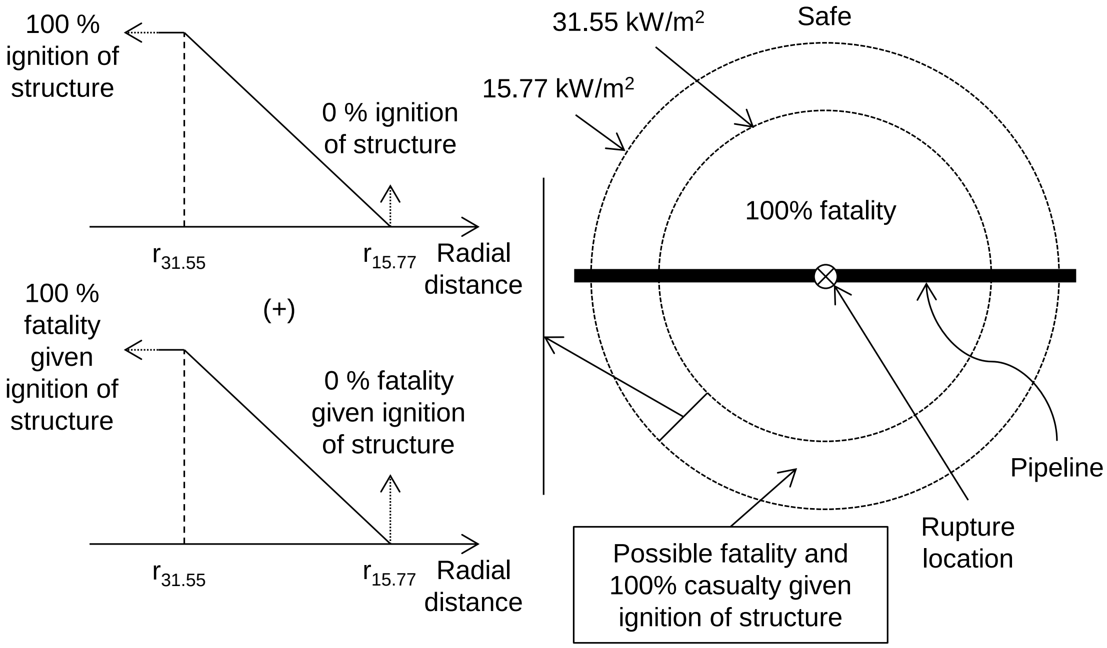

Figure 3: Thermal radiation intensity thresholds and human safety implications for indoor exposure

4 Case study of a hypothetical pipeline

4.1 Description of pipeline

A gas transmission pipeline is assumed to cross a residential area. The nominal pipe diameter (NPS) of the pipeline is assumed to be 24 inches (609.6 mm), and its operating pressure is assumed to be 6.0 MPa. In the residential area, it is assumed that there are many single-family houses (SglFamily), one meeting and recreation facility (MtgRecF), one school and several playgrounds (PlayGrnd). The assumed transmission pipeline and its surrounding buildings in the residential area are shown in Fig. 4.

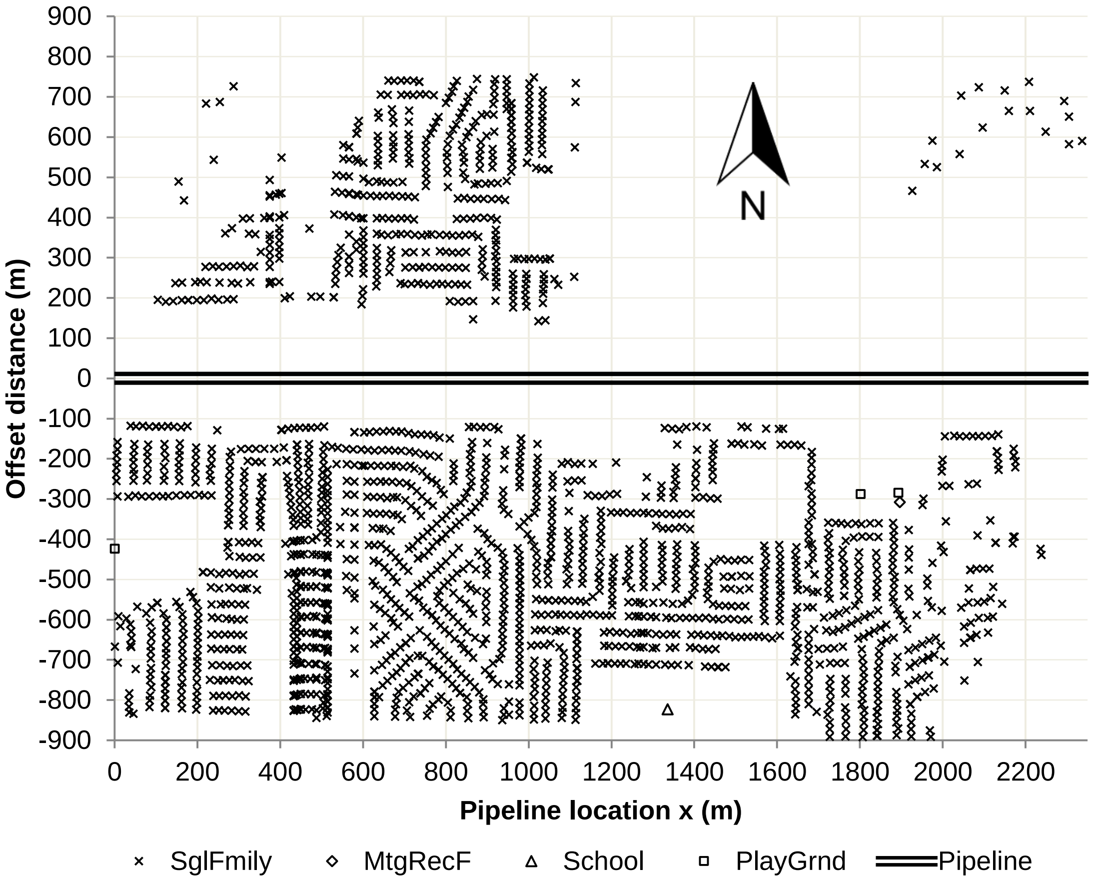

Figure 4: Illustration of a hypothetical pipeline and its surroundings

Through statistical analysis of onshore gas transmission pipeline incidents in the PHMSA data, it is found that the rupture rate of pipelines with diameters between 20 and 28 inches is about 2.5×10^{-5} per km-year. The obtained rupture rate is used as the representative rupture rate for the pipeline considered in this example. The POI of the assumed pipeline given a rupture is calculated to be 53% with the given pipeline diameter and operating pressure using Eq. (3).

Before estimating thermal radiation effect to the surrounding population due to an ignited rupture of the hypothetical pipeline, assumptions regarding the residency of the buildings near the pipeline need to be made. There are majorly four types of buildings in this example, i.e. single-family house, meeting and recreating facility, school, and playground. According to the census report of statistics Canada, the average number of people in a single-family house is assumed to be 2.9 based on the 2011 Census Report of Statistics Canada (Milan & Bohnert 2012). The probability of presence of people in the house at the time of incident is assumed to be 50%. The average number of people presenting in a meeting and recreation facility is assumed to be 100, and the facility is assumed to open 8 hours a day and 7 days a week. Therefore, the probability of presence of people in such a facility at the time of incident is 33.3%. The average number of people in a school is assumed to be 400 based on the data given in the overview of education in Canada by the council of Ministers of Education, Canada (access from http://www.cmec.ca/299/Education-in-Canada-An-Overview/), and the opening time of the school is assumed to be 8 hours a day and 5 days a week. Therefore, the probability of presence of people at the incident time is equal to 23.8%. The playground is assumed to be occupied 8 hours each day that the probability of presence of people at the incident time is equal to 33.3%, and the average number of people presenting in the playground is assumed to be 20. It is further assumed that people staying in a playground at the incident time are subjected to outdoor exposure, while those staying in a single-family house, meeting and recreation facility and school are subjected to indoor exposure. With the above assumptions, the thermal radiation effect to the surrounding population due to an ignited rupture of the pipeline can be calculated to estimate the societal risk level.

4.2 Result of risk analysis

The societal risk levels due to the hypothetical pipeline are calculated and shown in Fig. 5.

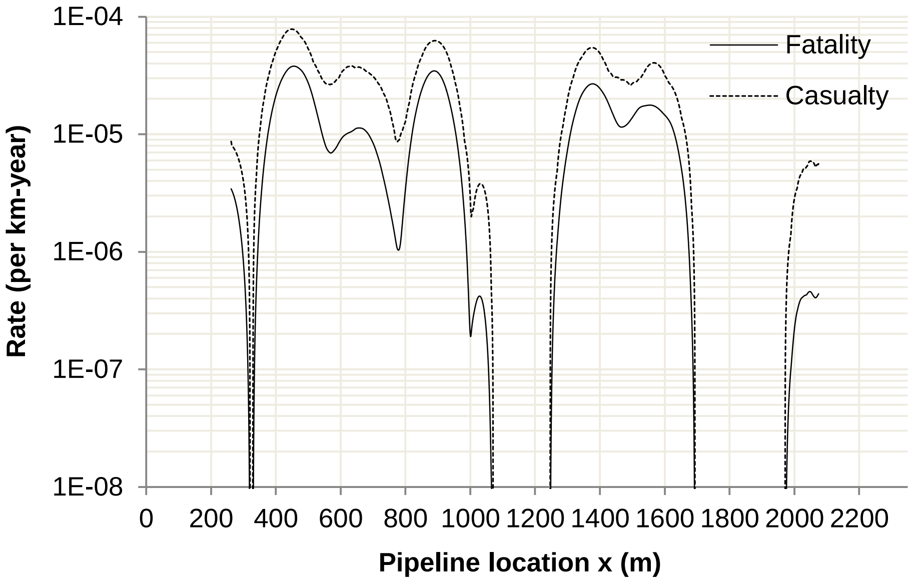

Figure 5: Societal risk level due to the pipeline

In Fig. 5, it is noticed that the societal risk levels in terms of fatality are the lowest at the pipeline locations around 1200 m and 1800 m, and relatively high at the pipeline locations around 500 m, 900 m and 1400 m. This can be explained by the distribution of buildings around the pipeline. In Fig. 4, at the pipeline locations around 1200 m and 1800 m, nearby buildings are located relatively farther (>200 m) from the pipeline compared to other portions of the pipeline. For the pipeline locations around 500 m, 900 m and 1400 m, the closest buildings are only about 100 m away from the pipeline, and thus the societal risk levels in terms of fatality in the locations are relatively high. The variation of the societal risk level in terms of casualty along the pipeline location is similar to that of the societal risk level in terms of fatality. The lowest and highest societal risk levels in terms of fatality are estimated to be 0 and 3.8×10^{-5} expected fatalities per km-year, respectively, while the lowest and highest societal risk levels in terms of casualty are estimated to be 0 and 7.8×10^{-5} expected casualties per km-year. From Figures 4 and 5, it can be inferred that the societal risk level is largely influenced by the relative locations between the pipeline and its surrounding buildings. If the offset distances of the buildings south of the pipeline are increased by just 5 m, the estimated maximum societal risk level in terms of fatality can be lowered to be 2.3×10^{-5} expected fatalities per km-year, leading to a 39% reduction of the risk level.

5 Conclusions

In this study, a log-logistic POI model for the rupture of onshore natural gas transmission pipelines is developed using maximum likelihood estimation based on the PHMSA gas transmission pipeline incident data between 2002 and 2014. The proposed POI model is employed in the quantitative risk assessment of a hypothetical onshore gas transmission pipeline considering the human safety-related societal risk. Thermal radiation effects caused by ignited ruptures of onshore gas pipelines are constructed using the well-known C-FER model for both the outdoor and indoor exposures. The results of the risk assessment indicate that the societal risk level is related to the relative locations between the pipeline and its surrounding buildings, and by increasing the offset distance between the population and pipeline, the societal risk level can be significantly reduced.

References

Acton, M.R. and Baldwin, P.J. 2008. Ignition probability for high pressure gas transmission pipelines. *In 2008 7th International Pipeline Conference*. American Society of Mechanical Engineers, pp. 331-339.

Bilo, M., and Kinsman, P. 1997. Thermal radiation criteria used in pipeline risk assessment. *Pipes & Pipelines International*, 42(6): 17-25.

Eisenberg, N.A., Lynch, C.J., and Breeding, R.J. 1975. Vulnerability Model: A Simulation System for Assessing Damage Resulting from Marine Spills.

Hymes, I. 1983. The physiological and pathological effects of thermal radiation. *Safety and Reliability Directorate*.

Lees, F.P. 1996. Loss prevention in the process industries: Hazard identification, assessment and control. Butterworth-Heinemann, Oxford, UK.

Milan, A. and Bohnert, N. 2012. Fifty years of families in Canada: 1961 to 2011. 98-312-X2011003, Minister of Industry, Ottawa.

Rodriguez, G. 2007. Lecture notes on generalized linear models chapter 3.

Rothwell, B. and Stephens, M. 2006. Risk analysis of sweet natural gas pipelines: Benchmarking simple consequence models. *In 2006 International Pipeline Conference*. American Society of Mechanical Engineers, pp. 911-919.

Stephens, M.J., Leewis, K. and Moore, D.K. 2002. A model for sizing high consequence areas associated with natural gas pipelines. *In 2002 4th International Pipeline Conference*. American Society of Mechanical Engineers, pp. 759-767.

Stephenson, B., Cook, D., Dixon, P., Duckworth, W., Kaiser, M., Koehler, K., and Meeker, W. 2008. *Binary Response and Logistic Regression Analysis*.

Zhou, W., and Nessim, M.A. 2011. Optimal design of onshore natural gas pipelines. *Journal of Pressure Vessel Technology*, 133(3): 031702.