

Modeling the Consequences of Pipeline Risk

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Abstract

Understanding the potential consequences of pipeline incidents is a critical component of pipeline risk management. By their very nature, these consequences are probabilistic – for any given potential incident, there is a range of the potential severity of the consequences that can arise. The severity of the consequences depends on both deterministic (e.g. line pressure, pipe size, etc.) and variable factors (e.g. how quickly is the leak located, is there an ignition source present at the time of the leak, etc.), which results in a distribution of potential outcomes with different likelihoods or probabilities. As a first step in understanding and modeling pipeline consequences, it is necessary to characterize the nature of this distribution – what is the potential range of consequences and their relative likelihoods? In this paper, the form of the distribution of consequences arising from pipeline incidents is examined and it is seen, in a variety of industries (gas distribution pipelines, gas transmission pipelines, hazardous liquid pipelines and gas gathering pipelines), to follow a power law or Pareto type distribution. This behavior has specific implications for both modeling and managing pipeline risk, particularly for the assessment and management of low probability-high consequence events.

Introduction

In managing a pipeline asset through its various life cycle stages, risk assessments are typically conducted to guide the decision making process. In this capacity, risk is typically defined as¹:

$$\text{Risk} = \text{Probability of Event} \times \text{Consequence of Event}$$

That is, the risk is a function of the probability of an event occurring times the consequence of that event. Risk, therefore, increases when there is either one or both of an increasing probability of an event occurring or an increasing consequence of that event.

When we are assessing risk for a pipeline, it is the future risk² that we are interested in; that is, what is the risk at some future point in time? – Tomorrow? Next year? Five years from now? Based on an assessment of these risks we can then make informed asset management decisions such as: Should a pipe segment be replaced? If so, how much of it should be replaced? What should be replaced first? How can we optimize our leak survey or in-line inspection program? Estimating these risks necessitates estimating the future probability of both events and consequences. In this paper, it is the projection of future consequences that is considered. That is, how can we project what the potential consequences of a pipeline leak could be?

Consequences of a Pipeline Incident

There is a broad range of potential consequences for a pipeline incident. From the PHMSA database for gas transmission pipeline incidents, the property damage for reported incidents ranges from a few thousand dollars to over \$350 million. Similarly, for gas distribution pipelines, reported property damage due to pipeline incidents ranges from a few thousand dollars to greater than \$42 million. While there are deterministic factors at play, such as pipe size, operating pressure and pipe location (e.g. HCAs³), there are also more random factors at play. For a gas distribution pipeline of the same size and operating pressure, for example, we can see leaks that result in very little consequence (e.g. those that are found by

¹ W. Kent Muhlbauer, *Pipeline Risk Management Manual*, 3rd Ed., Elsevier, 2004.

² For risk we are always talking about the future; something that has already occurred is not a risk, it is an event.

³ High Consequence Areas

leak survey and repaired prior to a significant event), leaks of moderate consequence (e.g. those where gas accumulation and ignition occurs with limited property damage), right through to significant incidents (e.g. major property damage with injuries and/or fatalities). Each of these consequences will have an associated probability. Some will be more likely than others – it is much more likely that a leak will be found and repaired than result in a significant incident, for example.

For a given future incident, therefore, there is a probability distribution of potential consequences that will be specific to the local environment surrounding that incident. In order to understand the risk associated with that incident, we need to understand this probability distribution. Likewise, for a pipeline system with multiple possible future leaks, there will be an overall probability distribution of potential consequences. It is the overall distribution that gives us insight into the true system risk. The question is, then, what do these potential consequence distributions look like and how do we estimate them?

Pareto Consequence Distributions in Pipeline Incidents – Power Law Behavior

In our work examining and modeling pipeline consequences, we observed that pipeline consequences appear to follow a very specific distribution. Pipeline consequences, along with many phenomena⁴ such as fire damage, earthquakes, floods and power blackouts, follow Power Law or Pareto-type distributions where a small number of incidents account for the majority of the overall damage and, hence, risk. This type of behavior is often referred to as the 80/20 rule (or Pareto's Law), where, for example, 80% of the damage comes from 20% of the incidents. While the specific ratios vary for different phenomena (95% of damage from 5% of incidents, 90% of damage from 10% of incidents, etc.), the concept is the same – a small number of events accounts for the majority of risk. This type of behavior gives rise to the low probability-high consequence events that can often dominate the risk picture.

Figure 1 shows the Power Law relationship for the frequency versus property damage for PHMSA⁵ reported gas distribution incidents in the US from 1992 to 2011, based on publicly available data from the PHMSA website⁶. The number of incidents resulting in different levels of property damage is shown for reported incidents with greater than \$100,000 damage. This lower bound was used to provide the best fit to the Power Law. This lower bound is believed to arise due to the requirements for size of incidents reported. The log⁷ of the frequency or number of events is plotted versus the log of the property damage that occurred for a total of 1095 reported incidents (the incident data for all causes) in a log-log plot. A strong Power Law relationship is observed with a 0.96 R² (96% of the data is described by the model). The same type of relationship is observed when the data is analyzed for individual utilities, by failure mode (e.g. third party damage, corrosion incidents, etc.). What this figure shows is that the majority of incident damage arises from a small number of incidents, as is typical for Power Law behavior.

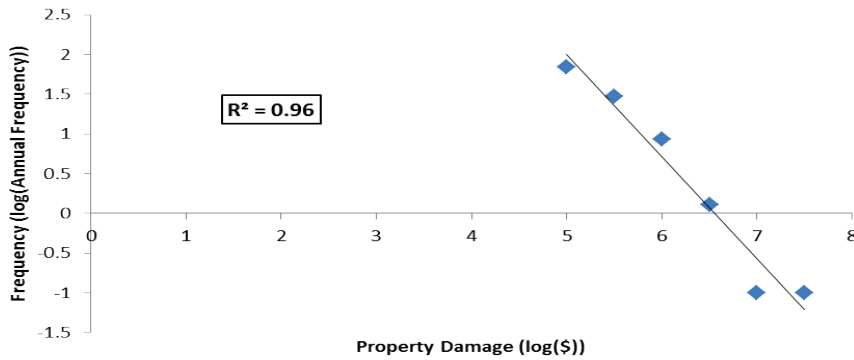
⁴ A. Clauset et al, *Power Law Distributions in Empirical Data*

⁵ Pipeline and Hazardous Materials Safety Administration

⁶ <http://primis.phmsa.dot.gov/comm/reports/safety/PSI.html>

⁷ The log or natural logarithm of a number is the exponent to which the base 10 must be raised to produce that number. For example, the log of 1,000 is 3, because 1,000 is 10 to the power 3: $1,000 = 10 \times 10 \times 10 = 10^3$. When data is plotted on a log scale, each increment is an order of magnitude higher than the previous – 1, 2, 3 on a log scale corresponds to 10, 100, 1,000 on a linear scale. A relationship that is exponential in nature will plot as a straight line on a log-log plot.

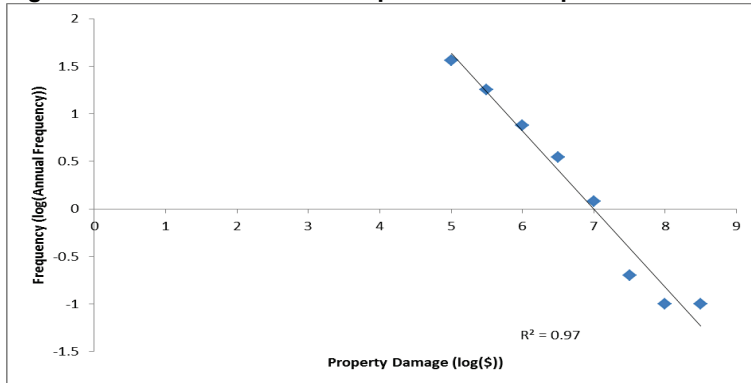
Figure 1: Power Law Relationship for PHMSA Reported Gas Distribution Incidents



Notes: Data plotted for reported pipeline incidents >\$100k damage for 1992-2011 PHMSA incident statistics⁸

Figure 2 provides the same plot for the PHMSA reported data for Gas Transmission incidents based on the data from 2002 to 2011. Again, strong Power Law behavior is observed, with an R^2 of 0.97 (97% of the data is described by the model).

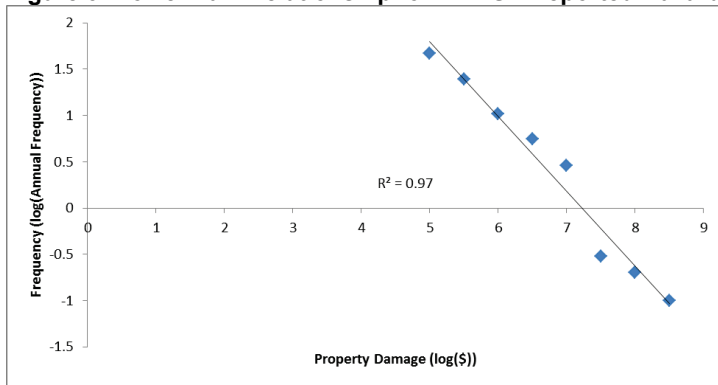
Figure 2: Power Law Relationship for PHMSA Reported Gas Transmission Incidents



Notes: Data plotted for reported pipeline incidents >\$100k damage for 2002-2011 PHMSA incident statistics⁸

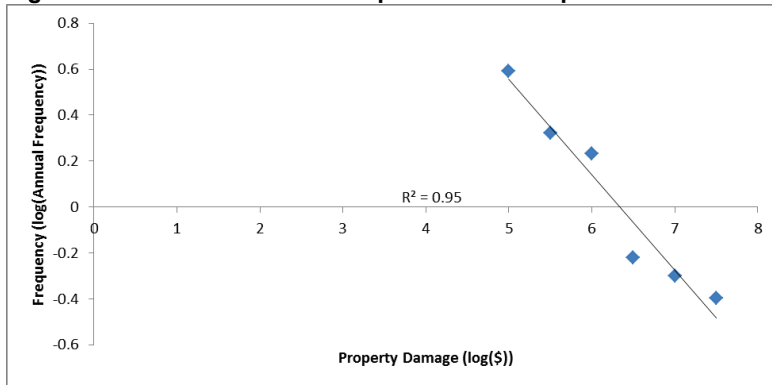
Figure 3 provides the same plot for the PHMSA reported data for Hazardous Liquid Pipeline incidents based on data from 2002 to 2011. Yet again, strong Power Law behavior is observed, with an R^2 of 0.97 (97% of the data is described by the model). **Figure 4** provides the data for gas gathering pipelines, with an R^2 of 0.95.

Figure 3: Power Law Relationship for PHMSA Reported Hazardous Liquid Pipeline Incidents



Notes: Data plotted for reported pipeline incidents >\$100k damage for 2002-2011 PHMSA incident statistics⁸

Figure 4: Power Law Relationship for PHMSA Reported Gas Gathering Pipeline Incidents



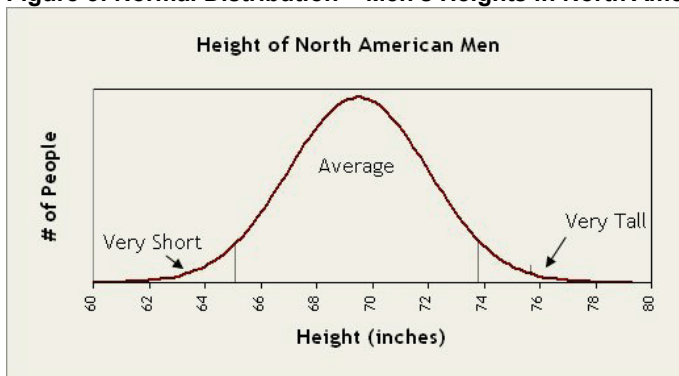
Notes: Data plotted for reported pipeline incidents >\$100k damage for 2002-2011 PHMSA incident statistics⁸

For four different pipeline industries: gas distribution, gas transmission, hazardous liquids and gas gathering, the same Power Law nature is observed for the distribution of incident size (measured in terms of PHMSA reported property damage) versus incident frequency. Similar Power Law behavior is observed for the distributions of number of injuries or fatalities versus frequency. Two key questions arise: how does power law behavior arise in pipeline incident consequences? And what does this mean for managing risk? After a brief discussion of the nature of Power Law distributions, both of these are addressed below.

The Nature of Power Law Distributions

Power Law distributions have a unique form that differs significantly from the normal (or Gaussian) distributions that we are more accustomed to dealing with in statistical analysis. A classic example of a normal distribution is the variation in the height of women or men. As shown in **Figure 5**, the distribution of heights of North American men is normally distributed with a mean (or average) of just under 70". The majority fall between 65" and 74", and a few hit the extreme tails around 62" and 78", but there is a very low probability of someone falling outside this range. The ratio of these extremes, the tall end of the range divided by the short end of the range, is 1.3 (the ratio for the tallest and shortest men on record is around 5). The variation is uniformly distributed relatively closely around the mean.

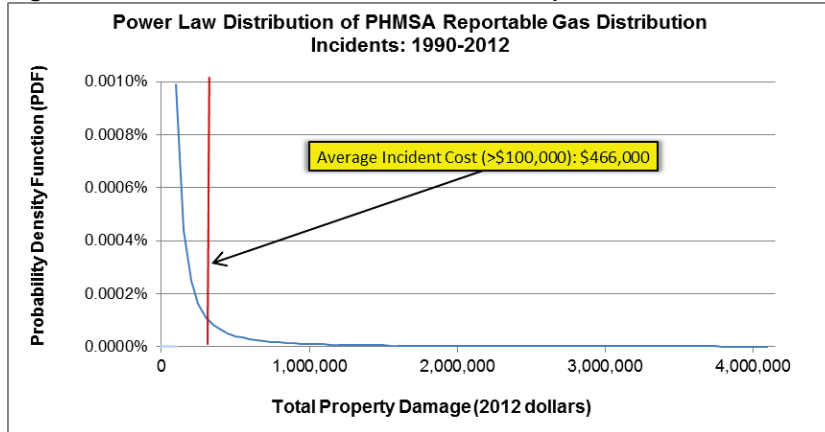
Figure 5: Normal Distribution – Men’s Heights in North America



In contrast, the power law distribution for gas distribution incidents is shown in **Figure 6**. Those for gas transmission, hazardous liquids and gas gathering follow the same general form. Instead of being symmetrically distributed around the mean value, as observed in the normal distribution, there is a long tail to the distribution. It is this long tail that represents the low probability-high consequence events. The ratio of the largest to the smallest (the low end of the distribution is cut off at \$100,000 due to the

artificial cut-off for reporting of incidents)⁸ is 430, indicative of the very broad range in potential consequences. The low probability-high consequence events dominate the risk picture – the top 20% of incidents is responsible for 60% of the property damage. The top 1% of incidents is responsible for 20% of the property damage.

Figure 6: Power Law Distribution for PHMSA Reported Gas Distribution Pipeline Incidents



Another key concept of distributions in general is that they describe a common population with common underlying drivers. Events that fall outside the distribution are outliers, impacted by factors other than those giving rise to the distribution. Once we define a distribution, therefore, we can use it to assess if a given incident is consistent with that distribution and hence part of the general population and driven by the same underlying factors or if the event is an outlier driven by other factors.

How Does Power Law Behavior Arise in Pipeline Incidents?

The mechanism underlying Power Law behavior in pipeline consequences is tied to the probability string that leads to a serious incident. Essentially, for a serious incident, there is a series of connected events that must occur, each with an associated probability: a leak, gas accumulation prior to location and repair, ignition, the presence of receptors (i.e. property, people, etc.), etc. Although the probabilities of each step vary with the specific environment, these are all essentially random events (for example, someone coming home after a leak to find gas accumulation in the house is a random event). It is the string of essentially random events, their associated consequences and their associated probabilities that results in Power Law behavior. All consequences are the result of a series of events occurring, each with an associated probability. Generally, the more severe the consequence, the longer the series of events that must occur, and mathematically the smaller the probability of that series occurring.

A simple analogy can be found in lotteries, which, whether we play them or not, we are all generally familiar with. While a lottery is what we could call a contrived⁹, or human-made system, it does provide a means of visualizing the Power Law nature of a string of probabilistic events. If we look, for example, at a lottery with six (6) numbers being drawn from a possible 49 numbers, we have a probability string leading to different outcomes as shown in **Figure 7**. To win, you need to have a ticket that matches a given number of the numbers drawn – the more numbers matched the greater the prize or consequence. There is a given probability for each step in the series of events¹⁰: $p(1)$ for getting one number, $p(2)$ for

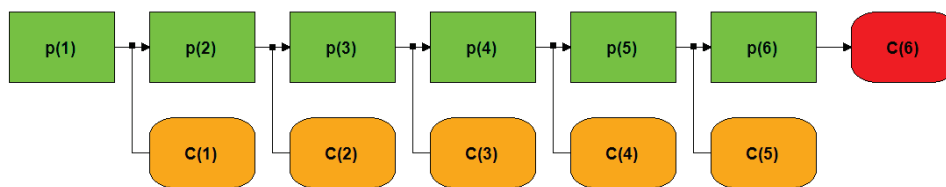
⁸ The PHMSA cut-off is \$50,000 in property damage. The incidents in the \$50k to \$99k range were excluded from the analysis as they do not fit the power law model for the rest of the distribution. This is likely a consequence of the reporting process.

⁹ Contrived in the sense that the prize money or consequences are set as a percentage of the overall pool of winning for each potential winning combination.

¹⁰ For this example, the lottery has 49 possible numbers, each number can only be drawn once and six numbers are drawn. The probabilities are, therefore: $6/49$ for the first number, $5/48$ for the second number, $4/47$ for the third number, $3/46$ for the fourth number, $2/45$ for the fifth

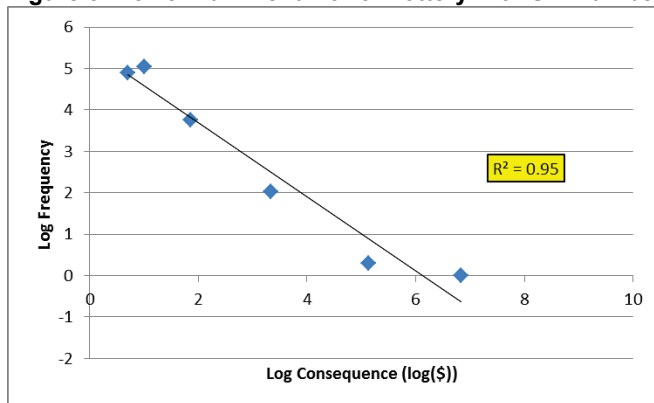
getting two numbers, $p(3)$ for getting three numbers, etc. If we get only one number right, we get consequence 1 ($c(1)$) – in the lottery example, nothing. If we get two numbers right, we get $c(2)$... three numbers right, $c(3)$... etc... all the way up to the big consequence, six numbers right. The probability of getting one number right is 0.12 ($6/49$)¹¹, or roughly 1 in 8. As we go through the probability string, the probabilities decrease and the consequences increase. The probability of getting two numbers right is the product of the probability of getting one number right ($6/49$) times the probability of getting a second number right ($5/48$)¹², or 0.013 (roughly 1 in 78). The probability of making it all the way through the probability chain – to getting all six numbers right and getting the big prize – is the product of the probabilities of getting one number times the probability of getting a second number times the probability of getting a third number, etc., and is very low. This is a low probability-high consequence event (the probability is 1 in 13,938,816).

Figure 7: Probability String for Lottery with Six Numbers Drawn



For a single event, we will have a single outcome – we will win the lottery (very unlikely), some money (a little more likely) or nothing (most likely). When we take the collection of all lottery players, we will have a distribution of outcomes that includes some winners (the minority) and some losers (the majority). It is in this distribution of the collection of outcomes that we see Power Law behavior. If we take the results from an actual lottery drawing¹³, the number of winners in each step of the probability string and their consequences (or winnings), we see that this distribution does indeed follow a Power Law relationship. The data for an actual draw from this lottery are provided in **Figure 8**. The data fit the power law with an R^2 of 0.95.

Figure 8: Power Law Behavior of Lottery with Six Numbers Drawn



While this is a simple example, it provides some insight into how Power Law behavior emerges when we have a collection of events occurring where the consequences of each event follows a probability string.

number and $1/44$ for the sixth number. The overall odds for getting all six numbers is the product of these probabilities: $(6/49)*(5/48)*(4/47)*(3/46)*(2/45)*(1/44) = 1$ in 13,938,816

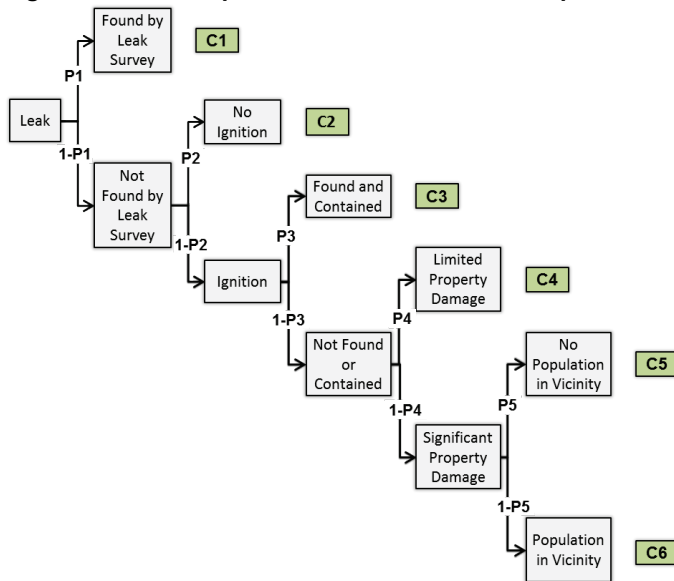
¹¹ We have six chances (since we picked six numbers) out of 49 possible numbers for getting one number right, or a probability of $6/49 = 0.12$

¹² For the second number, we have five chances (five of the original six choices are left) out of a possible 48 numbers (since one is already gone), or a probability of $5/48 = 0.104$

¹³ Lotto 649 – August 10th, 2013 results

We can use the same probability string in **Figure 7** and apply it to a gas distribution pipeline incident where, for example, one number = a leak found by leak survey, two numbers = gas accumulation without ignition (found by customer, for example), three numbers = ignition event, found and contained, four numbers = ignition event with limited property damage, five numbers = ignition event with significant property damage, six numbers = ignition event with people in vicinity (**Figure 9**). Although this is a crude representation, we can visualize how Power Law behavior can arise in pipeline incidents. For a single event or leak, we will have a given outcome, most likely a leak found by leak survey. When we look at multiple events, we will have a distribution of outcomes based on the probabilities and consequences in the probability string and, as we have seen, for pipeline incidents this distribution seems to closely follow the Power Law distribution.

Figure 9: Event Sequence for Gas Distribution Pipeline Incidents



With this understanding, it is now possible to develop Power Law relationships for pipeline incidents from industry-wide historical data and apply these to assessing risk in pipeline systems in a way that incorporates the potential for low probability-high consequence incidents. The distribution of consequences and their associated probabilities can be combined with leak forecast data to give an overall risk distribution for the pipeline. This gives us a tool for better managing the risk associated with the low probability-high consequence incidents that dominate the risk picture.

The Consequences of Power Law Behavior

There are two key considerations for risk management that come from this type of Power Law behavior. The first is that the low probability-high consequence events dominate the risk picture. These low probability-high consequence events are becoming more and more a focus in the pipeline industry. Power Law modeling provides a means of being able to better assess these low probability-high consequence events and, hence, manage them. As we see from the analysis of the PHMSA data for gas distribution pipelines discussed above, the top 1% of incidents account for 20% of the reported property damage. Similar statistics are observed for other pipeline categories. By understanding the nature and causes of the industry wide incidents in the top damage categories and how they relate to the smaller incidents, measures to thwart these larger incidents can be put in place. An example of this general approach at work can be seen in the Israeli counter-terrorism efforts – the size of terrorist attacks is another area that

follows Power Law behavior - where the implementation of specific strategies has sharply reduced the low probability-high consequence incidents relative to the smaller incidents¹⁴.

The second is that past behavior in these types of systems is not necessarily a good indicator of future risk. That is, a history of only low consequence events is not an indication that only low consequence events will continue to occur. In fact, Power Law behavior implies that with a significant number of low consequence events that there will be some associated number of higher consequence events that will eventually occur. This has been repeatedly observed in the pipeline industry where the same type of failure mode (e.g. corrosion, third party damage, etc.) that has previously resulted in only moderate incidents, results in an incident that causes significant damage, injuries or fatalities. Mapping the Power Law behavior of smaller incidents in terms of frequency and severity can actually be used to develop this specific relationship and allow prediction of the likelihood of the low probability-high consequence events. This can be used to allow pipeline operators to develop a more complete and accurate picture of the risks in their systems and, consequently, ensure that the proper asset management decisions are being made to contain risk.

Conclusions

The consequences of pipeline incidents are seen to follow Power Law or Pareto distributions. That is, there is a direct relationship between the frequency of incidents and their size, and the distribution of incidents has a form that leads to the low probability-high consequence events dominating the risk picture. This behavior is observed in a wide range of pipeline systems including gas distribution, gas transmission, hazardous liquid and gas gathering. Power Law modeling provides the capability to better assess the risk and, hence, manage that risk in pipeline systems. More specific analysis can also be applied for different incident types, such as third party damage, or incidents in high consequence areas, to provide further insights into risk management. The use of fault tree analysis of incident root causes to guide risk management is explored in a companion paper¹⁵.

¹⁴ Nate Silver, *The Signal and the Noise – Why So Many Predictions Fail but Some Don't*, 2012

¹⁵ Bryce, W, Oliphant, K. (2014). Managing Low Probability – High Consequence Pipeline Risk, in *Western Energy Institute Operations Conference*, April 22-24, 2014, Palm Springs, CA