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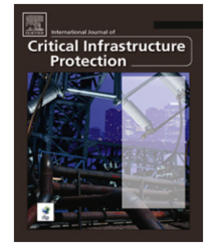

Causes, cost consequences, and risk implications of accidents in US hazardous liquid pipeline infrastructure

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ABSTRACT

In this paper the causes and consequences of accidents in US hazardous liquid pipelines that result in the unplanned release of hazardous liquids are examined. Understanding how different causes of accidents are associated with consequence measures can provide important inputs into risk management for this (and other) critical infrastructure systems. Data on 1582 accidents related to hazardous liquid pipelines for the period 2002–2005 are analyzed. The data were obtained from the US Department of Transportation's Office of Pipeline Safety (OPS). Of the 25 different causes of accidents included in the data the most common ones are equipment malfunction, corrosion, material and weld failures, and incorrect operation. This paper focuses on one type of consequence – various costs associated with these pipeline accidents – and causes associated with them. The following economic consequence measures related to accident cost are examined: the value of the product lost; public, private, and operator property damage; and cleanup, recovery, and other costs. Logistic regression modeling is used to determine what factors are associated with nonzero product loss cost, nonzero property damage cost and nonzero cleanup and recovery costs. The factors examined include the system part involved in the accident, location characteristics (offshore versus onshore location, occurrence in a high consequence area), and whether there was liquid ignition, an explosion, and/or a liquid spill. For the accidents associated with nonzero values for these consequence measures (weighted) least squares regression is used to understand the factors related to them, as well as how the different initiating causes of the accidents are associated with the consequence measures. The results of these models are then used to construct illustrative scenarios for hazardous liquid pipeline accidents. These scenarios suggest that the magnitude of consequence measures such as value of product lost, property damage and cleanup and recovery costs are highly dependent on accident cause and other accident characteristics. The regression models used to construct these scenarios constitute an analytical tool that industry decision-makers can use to estimate the possible consequences of accidents in these pipeline systems by cause (and other characteristics) and to allocate resources for maintenance and to reduce risk factors in these systems.

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1. Introduction

The network of pipelines that transport petroleum products and other hazardous liquids across the United States constitutes a critical infrastructure system that is vital to the country's energy supply and distribution, which in turn is a critical primer of the United States economy. About 66% of domestic petroleum moves through these pipelines [1]. Information about accidents related to these pipelines is collected by the Office of Pipeline Safety (OPS), a division of the US Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA). The OPS is also the safety authority for these pipelines. There are approximately 170,000 miles of hazardous liquid pipelines in the country [2]. According to current regulations (49 CFR 195.2), hazardous liquids include petroleum, petroleum products and anhydrous ammonia. Accidents are defined as "unplanned occurrences that result in the release of product from a hazardous liquid pipeline" [3]. Other pipelines monitored by the OPS but not included in this analysis provide natural gas transmission and distribution.

In this paper the relationship of characteristics and causes of accidents and system parts involved in hazardous liquid pipelines are analyzed in connection with one type of consequence — the costs associated with the accident. Although death and injury are key consequences, and have actually been monetized in other studies, e.g., electric power [4], the relative paucity of cases involving death or injury that involved these outcomes precludes a rigorous statistical analysis for these data.

Hazardous liquid pipeline accidents are required to be reported if they include an incident "in which there is a release of the hazardous liquid or carbon dioxide transported resulting in any of the following: (a) explosion or fire not intentionally set by the operator; (b) release of 5 gallons (19 liters) or more of hazardous liquid or compressed carbon dioxide; (c) death of any person; (d) personal injury requiring hospitalization; or (e) estimated property damage, including cost of cleanup and recovery, value of lost product, and damage to the property of the operator or others, or both, exceeding $50,000" [5, p. 67].

Hazardous liquid accidents are associated with a number of negative consequences, including deaths, injuries, environmental damage and various economic costs [5]. Although the number of deaths associated with these accidents is relatively low (a total of about 22 per year for the period 1989–1998) compared to the number of deaths associated with accidents in other transportation modes such as barge, rail or truck accidents [6], they are still of course important. Analyses of the spatial and temporal distribution of the frequency of occurrence of these accidents indicate important geographical differences [7].

There is a significant body of literature that has examined the probability of pipeline failures using various risk assessment methodologies. Dziubinski, Fratczak and Markowski [8], for example, provide several theoretical models to determine basic reasons for pipeline failures and their probable consequences. Yuhua and Datao [9] estimate failure probability using fault tree analysis. Metropolo and Brown [10] developed accident scenarios and used consequence analysis in order to investigate incidents and their consequences for natural gas pipelines, estimating distances from the incidents within which fatalities and injuries are likely to occur. Farrow and Hayakaw [11] have used a real options approach to provide a framework for optimal investment strategies to reduce costs associated with pipeline failures. Similar methodologies have also been used in Europe [12]. In addition, a number of studies using OPS and other datasets for the United States and Europe have focused on estimating the probability that a hazardous liquid and natural gas pipeline will fail given size and on trend analyses [13–15].

The work presented in this paper differs from those analyses in that it focuses on consequence measures related to cost, and how different initiating causes of the accidents, as well as different accident characteristics, affect those consequence measures. Such an approach is an important next step in identifying causes that have the greatest consequences as a basis for risk management. A two-step approach is used in the statistical analyses. In the first step the probability that there is a nonzero consequence associated with an accident is estimated as a function of the characteristics of the accident. In the second step the characteristics of the consequence measure are evaluated as a function of the characteristics of the accident, given that there is a nonzero outcome. The types of cost included in the analyses as consequence measures are (i) the value of the product lost; (ii) public, private, and operator property damage; and (iii) cleanup, recovery, and other costs.

Costs are often considered among the most important categories in ranking the importance of pipeline failures. Two of the six categories included in a 'gravity scale', for instance, are related to the cost of production losses and the cost of environmental cleanup [12]. The results of the models described in this paper can be used as inputs to risk models that require information about cost estimates and also input–output models that can be used to estimate the relationship and impact of specific sectors, such as oil and gas, on other economic sectors and the entire economy. Moreover, an advantage of the methodology used in this paper is that it can provide useful estimates of potential economic costs by using general accident data that are readily available without the need for the kinds of site- or pipeline-specific complex engineering computer models that are often used in assessing pipeline risks [16].

Risk assessment methodologies also consider costs and financial impacts as key factors. These methodologies typically estimate probabilities of pipeline failure outcomes, including financial costs, and expected values of those consequences if they occur [17]. The work presented in this paper follows this risk assessment approach in that a probability of nonzero cost occurrence given an accident is estimated and then, given that nonzero cost occurs, the expected cost consequence measures are computed. The methodology used in this paper also allows risk managers to identify factors that determine and quantify risk in a relatively straightforward way, which has been considered as a desirable outcome in the field of pipeline safety [6]. Other research in the area of infrastructure incident analyses has provided analogous results for other infrastructure

Table 1 – Commodities spilled in hazardous liquid accidents (10 or more accidents).

Commodity	Frequency	Percent
Crude oil	552	34.9
Gasoline	167	10.6
Propane	55	3.5
Diesel fuel	53	3.4
Unleaded gasoline	46	3.0
Crude	39	2.5
Petroleum crude oil	37	2.3
Diesel	34	2.1
Fuel oil	33	2.1
Anhydrous ammonia	27	1.7
Jet fuel	25	1.6
Transmix	18	1.1
Normal butane	16	1.0
Carbon dioxide	12	0.8
Propylene	12	0.8
Kerosene	11	0.7
Natural gasoline	10	0.6

Percentages do not add to 100% since commodities with fewer than 10 accidents do not appear in the table.

sectors [18,19,5]. As indicated earlier, although deaths and injuries are consequences of paramount importance, their low numbers make statistical analysis and prediction difficult to apply.

2. Methods

2.1. Data

The Hazardous Liquid Accidents data were obtained from the Office of Pipeline Safety (OPS) [20]. The period of analysis is January 2002 to December 2005, and includes information on 1582 accidents. Fig. 1 shows the monthly distribution and frequency of accidents during this period. Table 1 shows the products spilled in the accidents. The table only includes products involved in at least ten accidents.

Although OPS has maintained a database of accidents since 1970, the criteria for reporting accidents has changed several times since then [21]. The period 2002–05 is used because the criteria for reporting accidents was changed in 2002 and since then spills as small as 5 gallons are included [22]. The fact that accidents with such small spills are included in the database suggests that virtually all hazardous liquid pipeline accidents are included in the database and there is little or no selection bias in the data. In fact, Papadakis et al. [12] point to the OPS data collection process as a model for how the European Union should record and report pipeline accident data. Previous studies had found important limitations in the OPS data and recommended an increase in the number of cause categories [23]; since 2002 the reporting criteria have also included more detailed data on the cause of accidents, expanding this category to 25 causes [6]. The most common of these cause categories in the OPS data are corrosion, third-party excavation, ruptured or leaking seal/pump packing, and incorrect operation. Table 2 shows the causes included in the OPS database. Of the 1582

Table 2 – Causes of hazardous liquid accidents.

Accident cause	Frequency	Percent
Corrosion, external	119	7.5
Corrosion, internal	94	5.9
Miscellaneous	76	4.8
Third party excavation damage	66	4.2
Ruptured or leaking seal/pump packing	64	4.0
Incorrect operation	61	3.8
Component	45	2.8
Malfunction of control/relief equipment	45	2.8
Threads stripped, broken pipe coupling	30	1.9
Operator excavation damage	25	1.6
Unknown	22	1.4
Pipe seam weld	19	1.2
Body of pipe	16	1.0
Butt weld	15	0.9
High winds	15	0.9
Earth movement	13	0.8
Joint	13	0.8
Lightning	13	0.8
Car, truck or other vehicle not related to excavation activity	9	0.6
Fillet weld	9	0.6
Temperature	9	0.6
Rupture of previously damaged pipe	8	0.5
Heavy rains/floods	7	0.4
Vandalism	5	0.3
Fire/explosion as primary cause	2	0.1
No data	782	49.4
Total	1582	100

accidents included in the database for this period there is information on the cause for 800 accidents, or 50.6% of the total. The most common cause of accidents is external corrosion, which accounted for 14.9% of the accidents for which there was information on cause of the accident. Currently OPS does not include information about secondary causes of accidents. The inclusion of such information could help future researchers study how multiple causes affect the various consequence measures associated with hazardous liquid accidents, but such an analysis is not possible now.

The cost variables are all strongly right-skewed and as a result logged costs (the natural log of the value) were used in all of the models discussed in the paper. Of the 1582 accidents, 367 (23.2%) had zero product loss cost, 1109 (70.1%) had zero property damage cost, and 194 (12.3%) had zero cleanup cost. For these accidents logged cost is not defined, and such accidents are treated separately in the analyses as discussed in the next section. Similarly, the amount of liquid lost is very long right-tailed, and was analyzed in the natural log scale. This implies that all relationships with costs are multiplicative rather than additive, and all effects involving liquid lost are also multiplicative. There were 51 accidents for which no product loss was recorded. However, a significantly higher number of accidents had zero product loss cost even though product was spilled, because 100% of the product was recovered as part of the remediation efforts. All of the losses were either provided in gallons or converted to that unit.

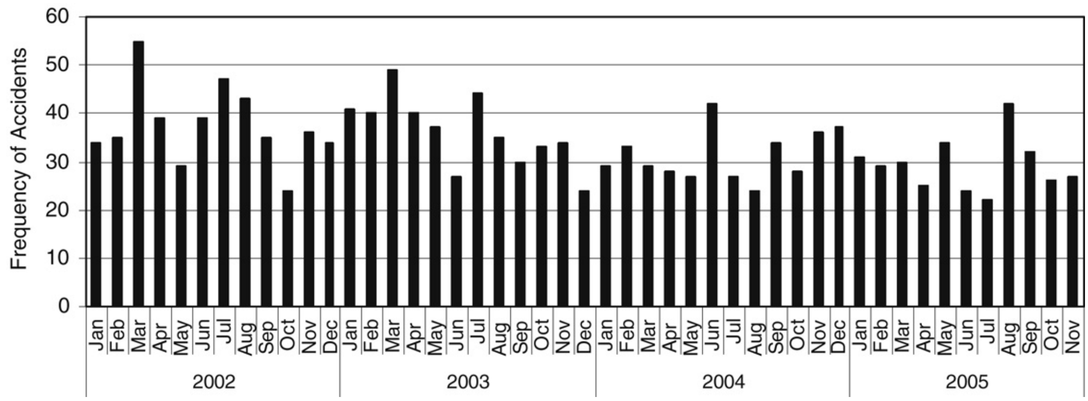

Fig. 1 – Monthly frequency of hazardous liquid accidents.

2.2. Methodology

A two-step approach is used in the statistical analyses. In the first step the probability that there is a nonzero consequence associated with an accident is estimated as a function of the characteristics of the accident. The response variable used in this first step for each consequence is binary and a logistic regression model is fitted to see which factors are predictive for whether or not there is product lost; public, private, and operator property damage costs; and cleanup, recovery, and other costs. Potential predictor variables include (logged) gallons of liquid lost, indicator variables for whether the accident occurred offshore, whether it occurred in a high consequence area, whether ignition of liquid occurred, and whether an explosion occurred, and categorical variables corresponding to the system part involved (which includes above ground storage tank, pump and meter station, onshore pipeline, offshore pipeline, and other part) and the accident cause (the different causes listed in Table 2).

In the results section a number of tables summarize the results of these models. Only numerical predictors with Wald statistics (the statistic analogous to a t-statistic in least squares regression) that are statistically significant at a .05 level are included in the final models summarized in the tables (with one exception; see Section 3.1.1). Categorical predictors (such as system part) have a p-value for the corresponding Wald test for the simultaneous significance of the entire effect (this is analogous to a partial F-test in least squares regression). This Wald test is based on a chi-squared distribution (rather than a normal distribution), so the actual test statistic is not comparable to the ones given for numerical predictors and is not given. Categorical predictors with overall Wald statistic significant at a .10 level are included in the final models. In addition to the overall Wald test for the categorical predictor, Wald tests for the significance of each level of the categorical predictor are given. These are based on effect codings, which means that the coefficients correspond to an effect of that level relative to the effect being taken into account with the level being "average". All of the levels of each categorical effect are included in the model, even if the effect corresponding to an individual level is not statistically significantly different from zero. The exponentiation of each coefficient is given in the tables under "Odds ratio", as these values correspond to the relative odds of a nonzero consequence. Note that if the predictor is numerical and in the logged scale the coefficient itself is an elasticity, and corresponds to the percentage change in the odds of nonzero consequence corresponding to a 1% change in the predictor, given all else is held fixed. Note also that since effect codings are used there is a coefficient for each level of a categorical predictor, something that does not occur when using indicator variables (since then the coefficient refers to the odds relative to the particular level that has been left out).

Probit regression models were also fit to all of the binary regression data, and the results were very similar to those obtained with logistic regression, as would be expected [24 (p. 394),25]). Only the results of the latter models are reported, as the logistic regression models provide easily-interpretable odds ratios.

In the second step of the analysis the characteristics of the consequence measure are examined as a function of the characteristics of the accident, given that there is a measurable outcome.

The response variables used in this part of the analysis (logged value of the product lost, logged public, private, and operator property damage, and logged cleanup, recovery, and other costs, respectively) are continuous and least squares regression models are fitted. The potential predictors in the model are the same as those used in the logistic regressions listed above, and variables are included in the final models based on the same criteria used in the logistic regressions (with t-statistics taking the place of Wald statistics for individual coefficients, and partial F-tests taking the place of Wald tests for categorical predictors).

For each regression in the second stage, the possibility of nonconstant variance was tested using Levene's test. Draper and Smith [26] describe Levene's test in the context of one-way analysis of variance data; the version used here is the natural generalization to multiple regression data. This test starts with the standardized residuals from the ordinary least squares fit, takes the absolute values, and uses that as the response in a regression. This is a test for nonconstant variance because higher variability corresponds to residuals that are larger in absolute value (that is, more positive and more negative).

To address nonconstant variance (if it exists), weights are determined based on the predictors associated with differences in variability, and a weighted least squares (WLS) model is fit. This is done by hypothesizing a model for the variances, and then estimating the parameters of the model from the data. The following approach was proposed and used in Simonoff and Tsai [27].

The standard model for variances is a multiplicative one, where the variance for ε_i, the regression model error term for the ith observation, is modeled as

$$\sigma_i^2 = \sigma^2[\exp(\gamma_0 + \gamma_1 z_{1i} + \gamma_2 z_{2i} + \cdots + \gamma_p z_{pi})], \quad (1)$$

where the z variables are those that are predictive for the variance. Thus, the model says that additive changes in z are associated with multiplicative changes in the variance. Poisson regression is used to estimate the parameters of this model (and thus make it possible to estimate the error variance for each observation by substituting in its values of the z variables). Since $\sigma_i^2 = E(\varepsilon_i^2)$, a regression model that posits a multiplicative (exponential) relationship between ε_i^2 and the z variables is consistent with Eq. (1), and the Poisson (loglinear) regression model is such a model. The ε_i^2 values are not available, since those are based on the unknown errors, but the standardized residuals from the original regression are available, which are the best guesses for those errors. Thus, the γ slope parameters from Eq. (1) are estimated using a Poisson regression model, where the response "counts" are actually the squared standardized residuals from the original OLS regression. These estimated coefficients then yield estimated variances for each observation; the inverse of this estimated variance is the weight for that observation.

3. Results

3.1. *Value of the product lost*

The first set of analyses refers to the value of the product lost during an accident. As was noted earlier, the analyses are first based on a logistic regression for the probability of nonzero product loss cost and then a least squares regression for the (logged) amount of product loss cost given that it is nonzero. A total of 76.8% of the accidents had nonzero product loss cost.

3.1.1. *Probability of nonzero product loss cost*

The first point to note in the binary regression fit is that if the model was fit on all of the observations there would be a problem, in that the data exhibit *complete separation* [24, p. 389]. This refers to the fact that for one type of cause predictors (vandalism), all of the accidents have nonzero product loss cost (there are five such accidents). This is because either no liquid was spilled, or all of the product was recovered. In this situation the model cannot be fit, because there is no logistic surface that corresponds to an estimated probability of nonzero damage of 0. Note that this is not actually a restriction on the usefulness of the model; all that needs to be done is to remove the observations that correspond to this level, because based on these data a perfect prediction is to say that it is always associated with nonzero product loss cost. That is, if an accident is caused by vandalism it is predicted to have nonzero product loss cost (of course, given the small number of accidents with vandalism as a cause, this cannot be viewed as a very strong effect, despite the complete separation). Otherwise, the logistic regression model is used to estimate the probability of nonzero product loss cost. Table 3 summarizes the results of the simplified logistic regression model that only includes important effects.

The results of the model indicate that holding all else fixed, a 1% increase in gallons lost is associated with a 0.2% increase in the odds that there will be nonzero product loss cost; an accident involving an above ground storage tank or "other" part is associated with lower odds of nonzero product loss cost; and an accident being offshore is associated with 85% lower odds of nonzero product loss cost (although this predictor is only marginally statistically significant, we have included it in the model because of its large effect on the odds of nonzero product loss cost). This last effect seems to contradict the earlier one concerning offshore pipeline accidents (and is only marginally statistically significant), but 6 of the 36 accidents involving offshore pipelines or platforms are listed as being located onshore, and all of them had nonzero product loss cost.

3.1.2. *Amount of product loss cost given that it is nonzero*

The initial ordinary least squares (OLS) model suggested there is nonconstant variance related to gallons lost and cause. The results of the weighted least squares regression model (fit using the method described in Section 2.2) suggest that only the variables related to logged gallons lost, offshore status, the presence of ignition, and cause categories are necessary. The results of the final model used for product loss cost are shown in Table 4. Note that the categorical predictor is again fit using effect codings, and a partial *F*-test is used to assess its overall statistical significance.

The model implies that holding all else fixed, a 1% increase in gallons lost is associated with a 0.86% increase in product loss cost; an accident offshore is associated with 86% higher product loss cost; and an accident involving an ignition of liquid has estimated product loss cost 1.9 times that of one that did not involve ignition. Note that the multiplicative nature of the model implies nonlinear relationships, where equal changes in the original predictor scale (gallons lost) are not associated with equal changes in the response scale (dollars). Causes with noteworthy relationships with product loss cost are third party excavation damage and pipe seam weld (higher cost), and internal corrosion, malfunction of control equipment, and ruptured or leaking seal (lower cost).

3.2. *Property damage costs*

The second set of analyses refers to property damage costs related to hazardous liquid pipeline accidents. Property damage includes public, private, and operator property damage. Once again, the probability of nonzero property damage is modeled first, and then its amount when that amount is nonzero. A total of 29.9% (473 of 1582) of the accidents had nonzero property damage costs.

Table 3 – Results of logistic regression model for probability of nonzero product loss cost.

Variable	Coefficient	Odds ratio	Std. error	z-value	Pr(>|z|)	Significance level
(Intercept)	0.247		0.348	0.71	0.478	
Logged gallons lost	0.191		0.038	5.04	0.000	***
Offshore	−1.881	0.152	1.173	−1.60	0.109	
System part involved					0.062	
Above ground storage tank	−0.634	0.531	0.339	−1.87	0.062	
Pump/meter station	0.084	1.087	0.280	0.30	0.765	
Other	−0.636	0.529	0.352	−1.81	0.070	
Onshore pipeline	−0.037	0.964	0.283	−0.13	0.897	
Offshore pipeline	1.223	3.396	0.937	1.31	0.192	

Null deviance: 747.22 on 754 degrees of freedom
Residual deviance: 699.59 on 748 degrees of freedom

*** Significance level: 0.001.
The odds ratio for Logged gallons lost is not given, since the coefficient itself represents an elasticity between gallons lost and the odds of nonzero product loss cost.

Table 4 – Results of weighted least squares model for logged product loss cost.

Variable	Coefficient	Semi-elasticity	Std. error	t-value	Pr(>|t|)	Significance level
(Intercept)	0.390		0.140	2.79	0.005	**
Logged gallons lost	0.859		0.018	49.01	<2e−16	***
Offshore	0.621	1.861	0.266	2.34	0.020	*
Ignition	0.658	1.930	0.236	2.79	0.006	**
Accident cause					0.000	***
Corrosion, external	0.169	1.184	0.113	1.50	0.134	
Corrosion, Internal	−0.541	0.582	0.138	−3.91	0.000	***
Earth movement	0.299	1.348	0.218	1.37	0.172	
Lightning	−0.259	0.772	0.246	−1.05	0.292	
Heavy rains/floods	−0.446	0.640	0.541	−0.83	0.410	
Temperature	−0.122	0.885	0.297	−0.41	0.682	
High winds	0.159	1.172	0.279	0.57	0.569	
Operator excavation damage	−0.294	0.745	0.277	−1.06	0.290	
Third party excavation damage	0.311	1.365	0.144	2.17	0.031	*
Fire/explosion as primary cause	0.397	1.488	0.243	1.64	0.102	
Car, truck or other vehicle not related to excavation activity	0.163	1.177	0.330	0.49	0.622	
Rupture of previously damaged pipe	0.495	1.640	0.331	1.49	0.136	
Vandalism	0.307	1.360	0.419	0.73	0.463	
Body of pipe	0.331	1.393	0.211	1.57	0.117	
Component	−0.232	0.793	0.238	−0.98	0.329	
Joint	0.141	1.152	0.282	0.50	0.616	
Butt weld	−0.226	0.798	0.389	−0.58	0.562	
Fillet weld	−0.192	0.826	0.428	−0.45	0.654	
Pipe seam weld	0.626	1.870	0.203	3.09	0.002	**
Malfunction of control/relief equipment	−0.261	0.771	0.150	−1.74	0.082	
Threads stripped, broken pipe coupling	−0.179	0.836	0.258	−0.69	0.488	
Ruptured or leaking seal/pump packing	−0.260	0.771	0.157	−1.65	0.100	
Incorrect operation	−0.126	0.882	0.150	−0.84	0.402	
Miscellaneous	−0.271	0.762	0.191	−1.42	0.156	
Unknown	0.010	1.010	0.223	0.05	0.964	

Multiple R-Squared: 0.9797, Adjusted R-squared: 0.9788
F-statistic: 1043 on 27 and 583 DF, p-value: $<2.2e{-16}$

The semielasticity for Logged gallons lost is not given, since the coefficient itself represents an elasticity between gallons lost and the product loss cost.
***Significance level: 0.001.
**Significance level: 0.01.
*Significance level: 0.05.

Table 5 – Results of logistic regression model for probability of nonzero property damage cost.

Variable	Coefficient	Odds ratio	Std. error	z-value	Pr(>|z|)	Significance level
(Intercept)	−0.890		0.125	−7.12	0.000	***
Ignition	1.198	3.315	0.386	3.10	0.002	**
System part involved					0.000	***
Above ground storage tank	−0.458	0.632	0.259	−1.77	0.077	
Pump/meter station	−0.145	0.865	0.162	−0.89	0.373	
Other	0.215	1.240	0.259	0.83	0.406	
Onshore pipeline	0.885	2.422	0.149	5.93	0.000	***
Offshore pipeline	−0.497	0.609	0.350	−1.42	0.156	

Null deviance: 1034.50 on 780 degrees of freedom
Residual deviance: 974.13 on 775 degrees of freedom

**Significance level: 0.01.
***Significance level: 0.001.

3.2.1. *Probability of nonzero property damage cost*

A logistic regression model is fit to see which factors are predictive for whether or not there are property damage costs. Table 5 shows the results. If an accident is caused by ignition, it is predicted to have nonzero property damage (this complete separation corresponds to only two accidents, so it cannot be taken very seriously). Otherwise, the logistic regression model is used to estimate the probability of nonzero property damage. The resultant logistic regression model shows that the only important factors in modeling whether or not there will be nonzero property damage are the system part involved and whether liquid ignited, highlighting that damage to onshore pipelines, and accidents where liquid ignited, are more likely to have nonzero property damage costs (accidents with liquid ignition have 3.3 times the odds of nonzero property damage costs), while damage to above ground storage tanks is less likely to have associated nonzero costs.

3.2.2. *Amount of property damage cost given that it is nonzero*

In this section the analysis of the factors related to nonzero property damage costs, given that there are nonzero costs, is presented. An OLS model for logged property damage indicates that all of the predictors other than the explosion indicator provide significant predictive power. In this case Levene's test does not provide any evidence of nonconstant variance, indicating that the OLS model is adequate. Table 6 summarizes the results of the model.

The model implies that holding all else fixed, a 1% increase in gallons lost is associated with a 0.19% increase in property damage cost; an accident that occurs in a high consequence area has an estimated property damage cost that is 2.9 times that of one not in such an area; an offshore accident is associated with 33.2 times the cost of one onshore; and an accident involving ignition of the liquid has an estimated cost 6.2 times that of one that did not involve ignition. High consequence areas include commercially navigable waterways, high population areas, and environmentally and unusually sensitive areas [28]. Causes with noteworthy associations with property damage cost include high winds and body of pipe (higher property damage), and external corrosion, operator excavation, component, control malfunction, threads stripped, and incorrect operation (lower property damage). Accidents associated with above ground storage tanks have higher property damage cost, and those associated with pump/meter stations have lower associated cost.

3.3. *Cleanup and recovery costs*

The third set of analyses carried out refers to cleanup and recovery costs related to hazardous liquid accidents. Once again, the probability of nonzero cleanup and recovery costs is modeled, and then its amount when that amount is nonzero. A total of 87.7% (1388 of 1582) of the accidents had nonzero cleanup and recovery costs. It should be noted that cleanup and recovery costs accounted for at least 75% of the total costs in more than 75% of the accidents, and accounted for at least 95% of the total costs in more than half of them, so this category of costs is particularly important from a risk management point of view.

3.3.1. *Probability of nonzero cleanup and recovery costs*

In this part of the analysis a logistic regression model is fit to see which factors are predictive for whether or not there are cleanup and recovery costs. The results of the model are summarized in Table 7. If an accident is caused by temperature (9 accidents), fire (2 accidents), butt weld (15 accidents), or fillet weld (9 accidents), or involves an above ground storage tank (72 accidents), it is predicted to have nonzero cleanup and recovery costs. Note that while the separation from different causes again corresponds to relatively few accidents, the larger number of accidents involving above ground storage tanks suggests a strong (and understandable) pattern that accidents involving above ground storage tanks will result in nonzero cleanup costs. Otherwise, the logistic regression model is used to estimate the probability of nonzero cleanup and recovery costs.

The output of the model shows that the cause and the high consequence area indicator are the important predictors. Given cause, being in a high consequence area is associated with 79% higher odds of nonzero cleanup and recovery costs. In addition to the causes that were always associated with nonzero cleanup and recovery costs, external and internal corrosion are associated with high probability of nonzero cleanup and recovery costs, and heavy rains, high winds, and unknown cause are associated with lower probability (given whether or not the accident is in a high consequence area).

Table 6 – Results of ordinary least squares model for logged property damage cost.

Variable	Coefficient	Semi-elasticity	Std. error	t-value	Pr(>|t|)	Significance level
(Intercept)	7.626		0.506	15.06	<2e−16	***
Logged gallons lost	0.192		0.053	3.65	0.000	***
High consequence area	1.059	2.883	0.279	3.80	0.000	***
Offshore	3.502	33.189	1.394	2.51	0.013	*
Ignition	1.828	6.218	0.588	3.11	0.002	**
System part involved					0.091	
Above ground storage tank	1.201	3.325	0.643	1.87	0.063	
Pump/meter station	−0.789	0.454	0.379	−2.09	0.038	*
Other	−0.631	0.532	0.468	−1.35	0.178	
Onshore pipeline	−0.367	0.693	0.337	−1.09	0.277	
Offshore pipeline	0.586	1.796	0.932	0.63	0.530	
Accident cause					0.014	*
Corrosion, external	−0.670	0.512	0.367	−1.83	0.069	
Corrosion, internal	−0.615	0.541	0.454	−1.35	0.177	
Earth movement	1.113	3.044	0.938	1.19	0.237	
Lightning	−0.091	0.913	0.822	−0.11	0.912	
Heavy rains/floods	−0.835	0.434	2.059	−0.41	0.686	
Temperature	0.872	2.391	1.978	0.44	0.660	
High winds	4.099	60.265	2.072	1.98	0.049	*
Operator excavation damage	−1.560	0.210	0.612	−2.55	0.011	*
Third party excavation damage	−0.502	0.605	0.446	−1.13	0.261	
Fire/explosion as primary cause	2.193	8.964	1.516	1.45	0.149	
Car, truck or other vehicle not related to excavation activity	0.971	2.639	1.019	0.95	0.342	
Rupture of previously damaged pipe	−0.059	0.943	1.212	−0.05	0.961	
Vandalism	−0.440	0.644	1.165	−0.38	0.706	
Body of pipe	1.792	6.004	0.805	2.23	0.027	*
Component	−1.145	0.318	0.533	−2.15	0.033	*
Joint	−1.115	0.328	1.164	−0.96	0.339	
Butt weld	0.575	1.776	0.728	0.79	0.431	
Fillet weld	0.208	1.231	1.531	0.14	0.892	
Pipe seam weld	0.647	1.910	0.617	1.05	0.295	
Malfunction of control/relief equipment	−2.163	0.115	0.795	−2.72	0.007	**
Threads stripped, broken pipe coupling	−1.734	0.177	0.665	−2.61	0.010	**
Ruptured or leaking seal/pump packing	−0.463	0.629	0.571	−0.81	0.418	
Incorrect operation	−1.155	0.315	0.601	−1.92	0.056	
Miscellaneous	−0.026	0.974	0.500	−0.05	0.958	
Unknown	0.103	1.109	0.898	0.12	0.909	

Residual standard error: 2.031 on 254 degrees of freedom
Multiple R-Squared: 0.3583, Adjusted R-squared: 0.2774
F-statistic: 4.431 on 32 and 254 DF, p-value: 6.056e-12

The semielasticity for Logged gallons lost is not given, since the coefficient itself represents an elasticity between gallons lost and the property damage cost.
***Significance level: 0.001.
**Significance level: 0.01.
*Significance level: 0.05.

3.3.2. *Amount of cleanup and recovery costs given that it is nonzero*

In this section the factors related to cleanup and recovery costs given that they are nonzero are presented. The initial regression models for logged cleanup and recovery costs indicated that all of the predictors other than the ignition and spill indicators provide significant predictive power. There was weak evidence of nonconstant variance from the Levene's test, related to cause and system part. Hence, a WLS regression model was used. Table 8 shows the values of the coefficients in the WLS model.

The model implies that holding all else fixed, a 1% increase in gallons lost is associated with a 0.25% increase in cleanup and recovery costs; an accident that occurs in a high consequence area has estimated cleanup and recovery costs that are 3.0 times that of one not in such an area; an offshore accident is associated with 12.6 times the recovery cost of an onshore accident; and an accident involving an explosion has estimated cleanup and recovery costs 88% lower than that of one that did not involve an explosion. Accidents involving pump/meter stations have lower cleanup and recovery costs than those involving other parts, while onshore pipelines are higher. Accidents related to earth movement, high winds, fire, rupture of previously damaged pipe, body of pipe, and pipe seam weld are associated with higher cleanup and recovery costs, while those related to internal corrosion, operator excavation, vandalism, control malfunction, threads stripped, ruptured or leaking seal, incorrect operation, or miscellaneous are associated with lower costs.

Table 7 – Results of logistic regression model for probability of nonzero cleanup and recovery costs.

Variable	Coefficient	Odds ratio	Std. error	z-value	Pr(>|z|)	Significance level
(Intercept)	1.514		0.171	8.87	<2e−16	***
High consequence area	0.582	1.790	0.286	2.04	0.042	*
Accident cause					0.031	*
Corrosion, external	0.805	2.236	0.366	2.20	0.028	*
Corrosion, internal	1.484	4.410	0.514	2.89	0.004	**
Earth movement	−0.428	0.652	0.648	−0.66	0.509	
Lightning	0.536	1.709	1.017	0.53	0.598	
Heavy rains/floods	−1.805	0.165	0.977	−1.85	0.065	
High winds	−1.359	0.257	0.556	−2.45	0.014	*
Operator excavation damage	−0.061	0.941	0.545	−0.11	0.911	
Third party excavation damage	0.289	1.335	0.393	0.74	0.462	
Car, truck or other vehicle not related to excavation activity	0.513	1.670	1.023	0.50	0.616	
Rupture of previously damaged pipe	−0.685	0.504	0.800	−0.86	0.392	
Vandalism	−0.336	0.715	1.081	−0.31	0.756	
Body of pipe	−0.413	0.662	0.640	−0.64	0.519	
Component	−0.355	0.701	0.411	−0.86	0.389	
Joint	0.780	2.182	1.005	0.78	0.438	
Pipe seam weld	1.196	3.306	0.991	1.21	0.228	
Malfunction of control/relief equipment	0.436	1.546	0.529	0.82	0.410	
Threads stripped, broken pipe coupling	−0.191	0.826	0.497	−0.38	0.702	
Ruptured or leaking seal/pump packing	0.140	1.150	0.378	0.37	0.712	
Incorrect operation	0.146	1.158	0.419	0.35	0.727	
Miscellaneous	0.309	1.363	0.416	0.74	0.457	
Unknown	−1.002	0.367	0.510	−1.96	0.050	*

Null deviance: 543.03 on 693 degrees of freedom
Residual deviance: 503.57 on 672 degrees of freedom

***Significance level: 0.001.
**Significance level: 0.01.
*Significance level: 0.05.

3.4. *Evacuation status*

A final response variable considered is whether or not an evacuation is ordered during an accident. Although the number of people evacuated is also recorded in the database, the magnitude of this variable presumably depends on the geographic location of the accident, rather than its actual characteristics. Hence, evacuation is modeled as a dichotomous variable in this section. Evacuation status was only recorded for 805 accidents and an evacuation was only called for in 6.1% of those events.

A logistic regression model is fit in order to understand which factors are predictive for whether or not there is an evacuation called. Once again the observations that correspond to the levels with complete separation need to be identified and removed. This implies that if an accident is either (1) offshore (33 accidents); or (2) does not involve a liquid spill (11 accidents); or (3) is caused by heavy rains or floods (7 accidents), temperature (9 accidents), high winds (15 accidents), control equipment (45 accidents), threads stripped (30 accidents), or miscellaneous (76 accidents), it is predicted to not result in an evacuation. In the resultant model the explosion indicator is insignificant, and the ignition one is marginal. Once the explosion indicator is omitted, the cause effect is no longer statistically significant and once cause of accident is omitted, all of the other effects are highly statistically significant.

The output in Table 9 shows that holding all else fixed, a 1% increase in gallons lost is associated with a 0.28% increase in the odds of evacuation; an accident in a high consequence area has 2.3 times the odds of requiring evacuation; an accident with ignition has 6.7 times the odds of requiring evacuation; and accidents involving an onshore pipeline are more likely to require evacuation, while those involving pump/meter stations are less likely to do so.

4. Scenarios and sensitivity analyses

The results of the methodology presented in this paper can be used to construct accident scenarios that could be used as inputs to risk management in the oil sector. In this section of the paper a number of illustrative scenarios are included to show how such scenarios can be compared to each other and used to gain a better understanding of how sensitive predictions of consequence measures are to variations in the variables included in the models. The association between consequence measures and the various variables considered in these models can also provide some guidance to resource allocation for security purposes. An analogous exercise was done for the electricity sector using data on electric power failures [19,4].

Table 10 shows a number of illustrative scenarios for hazardous liquid pipeline accidents. They indicate that the values of consequence measures such as value of product lost, property damage cost and cleanup and recovery costs vary greatly depending on accident cause and other

Table 8 – Results of weighted least squares model for logged cleanup and recovery costs.

Variable	Coefficient	Semi-elasticity	Std. error	t-value	Pr(>|t|)	Significance level
(Intercept)	8.671		0.275	31.48	<2e−16	***
Logged gallons lost	0.245		0.026	9.33	<2e−16	***
High consequence area	1.094	2.986	0.144	7.62	0.000	***
Offshore	2.533	12.592	0.937	2.70	0.007	**
Explosion	−2.116	0.120	0.418	−5.07	0.000	***
System part involved					0.000	***
Above ground storage tank	−0.283	0.754	0.266	−1.06	0.289	
Pump/meter station	−0.437	0.646	0.197	−2.22	0.027	*
Other	0.175	1.191	0.263	0.67	0.506	
Onshore pipeline	0.405	1.499	0.206	1.96	0.050	
Offshore pipeline	0.139	1.150	0.647	0.22	0.829	
Accident cause					<2.2e−16	***
Corrosion, external	−0.174	0.840	0.217	−0.80	0.423	
Corrosion, internal	−0.834	0.434	0.199	−4.19	0.000	***
Earth movement	2.071	7.935	0.334	6.21	0.000	***
Lightning	−0.186	0.830	0.577	−0.32	0.747	
Heavy rains/floods	−0.182	0.834	0.629	−0.29	0.772	
Temperature	0.523	1.688	0.462	1.13	0.257	
High winds	1.872	6.498	0.787	2.38	0.018	*
Operator excavation damage	−0.919	0.399	0.384	−2.39	0.017	*
Third party excavation damage	−0.171	0.843	0.243	−0.71	0.481	
Fire/explosion as primary cause	1.863	6.443	0.372	5.00	0.000	***
Car, truck or other vehicle not related to excavation activity	0.166	1.181	0.603	0.28	0.783	
Rupture of previously damaged pipe	1.418	4.127	0.412	3.44	0.001	***
Vandalism	−1.296	0.274	0.694	−1.87	0.062	
Body of pipe	0.923	2.518	0.423	2.18	0.029	*
Component	−0.245	0.783	0.269	−0.91	0.364	
Joint	−0.670	0.512	0.556	−1.21	0.229	
Butt weld	0.773	2.167	0.571	1.35	0.177	
Fillet weld	0.727	2.068	0.583	1.25	0.213	
Pipe seam weld	0.804	2.235	0.347	2.32	0.021	*
Malfunction of control/relief equipment	−1.750	0.174	0.326	−5.37	0.000	***
Threads stripped, broken pipe coupling	−1.557	0.211	0.325	−4.79	0.000	***
Ruptured or leaking seal/pump packing	−1.066	0.344	0.321	−3.33	0.001	***
Incorrect operation	−1.071	0.343	0.220	−4.87	0.000	***
Miscellaneous	−0.633	0.531	0.233	−2.71	0.007	**
Unknown	−0.387	0.679	0.668	−0.58	0.563	

Multiple R-Squared: 0.5045, Adjusted R-squared: 0.4794
F-statistic: 20.14 on 32 and 633 DF, p-value: <2.2e−16

The semielasticity for Logged gallons lost is not given, since the coefficient itself represents an elasticity between gallons lost and the cleanup and recovery costs.
***Significance level: 0.001.
**Significance level: 0.01.
*Significance level: 0.05.

factors. The dollar amounts presented in the table for these consequence measures are the mid-point of a 50% prediction interval (the interval is constructed in the logged cost scale, and then anti-logged). The lower and upper bounds of the 50% prediction interval are shown in parentheses, and define an interval within which the cost is predicted to fall with 50% probability. The estimated probability of the scenario resulting in nonzero cost in each case is also given. In order to understand how sensitive the results are to changes in the inputs consider the first two scenarios. Each one results in a spill of 420,000 gallons of hazardous liquid but the initiating causes of the spills are different. The first is caused by internal corrosion of the pipeline and the second one by third party excavation. The second one takes place in a high consequence area (i.e., high population density or sensitive environmental area) and involves liquid ignition and an explosion. This second scenario has much higher value of product loss and property damage, and a higher probability of nonzero property damage cost, whereas the first has a higher cleanup and recovery cost.

5. Conclusions

The transport of petroleum products and other hazardous liquids is crucial to the energy sector and the US economy. In this paper data on accidents in hazardous liquid pipelines as provided by the Office of Pipeline Safety (OPS) are analyzed. This research work uses the latest data from OPS, which includes more detailed cause categories than previous data

Table 9 – Results of the logistic regression model to see which factors are predictive for whether or not an evacuation is called.

Variable	Coefficient	Odds ratio	Std. error	z-value	Pr(>|z|)	Significance level
(Intercept)	−5.658		0.716	−7.91	0.000	***
Logged gallons lost	0.276		0.072	3.84	0.000	***
High consequence area	0.840	2.315	0.330	2.54	0.011	*
Ignition	1.906	6.726	0.568	3.36	0.001	***
System part involved					0.015	*
Above ground storage tank	−0.064	0.938	0.631	−0.10	0.920	
Pump/meter station	−1.320	0.267	0.606	−2.18	0.030	*
Other	0.424	1.529	0.572	0.74	0.459	
Onshore pipeline	0.959	2.609	0.347	2.77	0.006	**

Null deviance: 334.49 on 571 degrees of freedom
Residual deviance: 264.12 on 565 degrees of freedom

The odds ratio for Logged gallons lost is not given, since the coefficient itself represents an elasticity between gallons lost and the odds of evacuation.
***Significance level: 0.001.
**Significance level: 0.01.
*Significance level: 0.05.

used in other studies that have looked at the association between cause of accidents and costs [23]. The statistical analyses and regression models presented in this paper show important associations between different characteristics of the accidents and the consequence measures that go along with them. The consequence measures included in the analyses were the value of the product lost, public, private, and operator property damage, and cleanup, recovery, and other costs. The factors that influence the magnitude of these consequence measures are the characteristics of the accidents such as explosion, product ignition, amount of liquid lost, the area where the accidents took place such as high consequence area and offshore, the system part involved, and the cause of the accident, and these potential factors clearly have different relationships with the different types of costs.

The results of the analyses suggest that the amount of liquid lost is a strong predictor for all responses — product loss cost, property damage cost, cleanup and recovery costs, and whether an evacuation is needed. At the lowest extreme, accidents where no liquid is lost are associated with no need for evacuation. Accident cause is an important predictor for all responses. The term “high consequence area” seems appropriate, as accidents in such areas have higher property damage when it is nonzero, higher chance of nonzero cleanup and recovery costs, higher cleanup recovery costs when they are nonzero, and a higher chance of requiring an evacuation.

Offshore accidents do not involve evacuation, but they are associated with a higher chance of nonzero product loss costs, higher product loss costs when they are nonzero, higher property damage (coming from operator property damage, since there is no public/private property damage offshore), and higher cleanup and recovery costs, presumably related to the logistical difficulties in getting repair and cleanup equipment to the accident site.

Liquid ignition is associated with higher product loss costs, higher odds of nonzero property damage costs, higher property damage cost when it is nonzero, and an increased chance of evacuation. Accidents related to above ground storage tanks are associated with lower chances of nonzero product loss costs, but higher property damage and higher odds of nonzero cleanup and recovery costs (indeed, all such accidents in the database had nonzero cleanup and recovery costs). Injuries or fatalities from hazardous liquid accidents during 2002–2005 were very rare.

The results also show that there is significant variation in the consequence measures examined depending on the factors affecting the accidents. As Table 10 shows, the results of the regression models used in the analyses allow for the construction of accident scenarios. This kind of scenario analysis can help industry risk analysts to better understand how different factors affect the magnitude of a potential hazardous liquid accident. As such, these models can provide important inputs to risk management in the oil industry and can be viewed as complementary to other risk management approaches such as the precautionary principle [11]. In addition, these models and scenarios can provide important inputs to research funding decisions such as the US Department of Transportation’s Pipeline Safety Research Program, which aims to incorporate risk-based approaches into pipeline regulations [29]. The methodology presented in this paper could also be applied to data sets for other geographical regions, such as the European Union.

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Table 10 – Scenarios for hazardous liquid pipeline accidents.

Cause	High consequence area?	System part involved	Onshore/ offshore	Did liquid ignite?	Was there an explosion?	Amount spilled (gallons)	Value of product lost (US$ '000) with probability of nonzero value	Property damage (US$ '000) with probability of nonzero value	Cleanup and recovery (US$ '000) with probability of nonzero value	Total cost estimates assuming all costs occur (US$ '000)
Internal corrosion	No	Onshore pipeline	Onshore	No	No	420,000	$58 ($16, $205) 0.936	$9 ($2, $36) 0.499	$90 ($28, $282) 0.952	$157($ 46, $523)
Third party excavation	Yes	Onshore pipeline	Onshore	Yes	Yes	420,000	$264 ($107, $645) 0.936	$186 ($47, $733) 0.767	$63 ($22, $174) 0.916	$513 ($176, $1552)
Control equipment malfunction	Yes	Storage tank	Onshore	Yes	Yes	1,260,000	$383 ($141, $1037) 0.909	$210 ($53, $825) 0.463	$8 ($2, $44) 0.904	$601 ($196, $1906)
High winds	Yes	Offshore pipeline	Offshore	No	No	840,000	$396 ($252, $624) 0.900	$292,796 ($74333, $1153323) 0.200	$46,174 ($11632, $183285) 0.884	$339366 ($86217, $1337232)
Incorrect operation	Yes	Onshore pipeline	Onshore	Yes	Yes	840,000	$309 ($113, $845) 0.944	$111 ($28, $436) 0.767	$30 ($11, $82) 0.916	$450 ($152, $1363)

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