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Accident occurrance evaluation in the pipeline transport of dangerous goods

Chiara BERSANI[a], Lucia CITRO[b], Roberta V. GAGLIARDI[b], Roberto SACILE[a], Angela M. TOMASONI[a,c]
[a]DIST, Department of Communication, Computer and System Sciences, University of Genova, Via all'Opera Pia 13, 16145 Genova, Italy
[b]ISPESL Department Industrial Premises and Interaction with the Environment, Via Urbana 167, 00184 Rome, Italy
[c]MINES ParisTech, CRC - Centre for Research on Risk and Crises, BP 207, 1 Rue Claude Daunesse 06904 Sophia Antipolis Cedex, France

A pipeline is a complex system, geographically spread on a wide territory, requiring technologies and methodologies to support the identification of pipeline segments that are highly potentially at risk of failure. This paper tackles a dual problem: to describe the most significant causes that may lead to a pipeline segment failure; to evaluate the occurrence of these causes leading to a failure, according to technical characteristics of the pipeline, infrastructures, territorial elements, and land use activities in the pipeline neighbourhood. This analysis constitutes the methodological basis to implement a Geographic Information System to support decisions as regards risk analysis and land planning criteria.

1. Introduction

Natural gas, crude oil and petroleum products represent the main products transported by pipeline networks. The total length of European High Pressure networks for natural gas transport was approximately 200,000 km in 2003, compared to ~180,000 km in 1996 [Eurogas, (2005), "Brochure: Natural gas - the energy for a sustainable future", available at: www.eurogas.org]. The combined traffic volume in the CONservatio of Clear Air and Water in Europe (CONCAWE, the oil companies' European association for environment, health and safety in refining and distribution) system in 2001 was 131 billion cubic meters/km, of which ~70 % was crude oil (16 % higher than in 1994). A network of ~10, 000 km pipelines convey more than 150 different hazardous materials such as: ethylene, propylene, chlorine, ammonia, hydrogen, oxygen, butadiene and styrene, (Papadakis, 1999). In Europe, the quantity of oil transported by pipeline increased of 10% in 2006 compared to 2000 [Eurostat, (2008), "Statistics in focus, Transport, 35/2008", available at: http://epp.eurostat.ec.europa.eu/portal/page/portal/transport/data/database]. In total, 526 Mm3 of crude oil and 279 Mm3 of refined products were transported by pipeline in Europe in 2006 [CONCAWE, (2008), "Performance of European cross-country oil pipelines, Statistical summary of reported spillages in 2006 and since 1971, 7/2008"]. In

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Italy, the overall length of pipelines for the transport of oil products is estimated to 4179 km in 2006 [Eurostat, (2009), available at: http://epp.eurostat.ec.europa.eu/portal/page/portal/transport/data/database].
Generally, pipeline transport risk is defined as the product of the probability of leakage or bursting and the related magnitude (Muhlbauer W.K., 1996). Moreover, in this context, an accident is classified according to the probability that a loss (or release), a hole or a rupture can occur in a pipe (Cooke et al., 2002). So, in a quantitative risk analysis, safety and security must be evaluated by decision makers and planners both analytically and statistically.In this paper, the problem is to evaluate the occurrence of a failure in a pipeline. From a statistical point of view, the main issue is represented by the collection and analysis of data about accidental events occurred in similar pipeline over the years taking into account information relevant to construction and operation elements, and various technological, operative and environmental features of the selected pipes. This statistical analysis is a hard task due to the fact that, auspiciously, pipeline failures are extremely rare events. Hereinafter, the main type of accidents in a pipeline are described, as well as the main factors that directly or indirectly may lead to them. Then, a methodological approach based on Artificial Neural Networks and preliminary results are shown for the case of accidents due to third parties activities.

2. Types of accident

Several types of accidents have been identified by the gas and oil pipeline industry in the past according to US Department of Transportation (DOT) Office of Pipeline Safety, 1991 and CONCAWE 1996 (Papadakis, 1999). They are most frequently classified in five cause categories: *Third parties* that represent a damage caused by operations carried out by others in the pipeline vicinity and not related to its management; *Corrosion*, when pipeline is subject to two types of corrosion, the first one is an inside corrosion, derived from water or other substances transported with hydrocarbons (viscosity and temperature are crucial information for the accident analysis), the second one is an outside corrosion related to the pipe coating and cathodic protection; *Mechanical* that are fractures or cracks that occur when efforts go beyond the efforts of the system permits; *Operational error*, which are caused by excessive pressure or system malfunction; *Natural events* such as landslides, floods, erosion in general, subsidence, earthquakes, frost or lightning. On the bases of CONCAWE [CONCAWE, (2008), "Performance of European cross-country oil pipelines, Statistical summary of reported spillages in 2006 and since 1971, 7/2008"] and DOT statistics [DOT, (2009), available at: http://primis.phmsa.dot.gov/comm/reports/safety/SIDA.html?nocache=8171] in a time period of twenty five years data (1971-1996) the cause of accident can be classified as follows:

Table I. Relevant causes leading to an accident or failure and their percentage.

	CONCAWE[%]	DOT[%]
Third Parties	33	34
Corrosion	30	33
Mechanical	25	18
Operational Errors	7	2.5
Natural Events	4	4.5
Others	1	8

In this work, three causes of accident (corrosion, mechanical, third parties) have been taken into account, first of all, since the percentages from CONCAWE and DOT are comparable and because the sum of their percentage value (88% for CONCAWE and 85% for DOT) has a statistical significance.

3. Factors leading to an accident

Several works present in the literature (among others Cooke, et al., 2002, Mazzucchelli et al., 1999 and Muhlbauer W. D., 1996) have analyzed the factors that may lead, either directly or indirectly, to a pipeline failure and to a related accident. These factors can be grouped into three main subsets: hydrological, anthropogenic, and technical factors (table II). Table III shows the factors which are mainly related to a pipeline failure respectively for corrosion, mechanical, third parties causes (Mazzucchelli at al., 1999).

Table II. Main factors leading to a cause of accident.

Hydrogeological factors	Anthropogenic factors	Technical factors
1. Crossing of rivers 2. Groundwater depth 3. Zone of landslide 4. Lithology divided in four classes: -Bedrock -Weathered rock -Alluvial coarse deposits -Alluvial fine deposits 5. Soil permeability divided in four classes: -A: Deep sands and rapidly permeable gravel, with very little silt and clay -B: Mostly sandy soils less deep and aggregated than A -C: Shallow soils and soil containing considerable clay and colloids. -D: Mostly clays of high swelling percentage and/or with nearly impermeable sub-horizons near the surface.	1.Land use (six classes): -Farmland: grass, crops -Farmland: trees -Woodland -Quarries & bare ground -Urban areas -Surface water 2.Population density (habitants/km^2) 3. Street crossing 4. Railways crossing 5.Sewage systems crossing 6. Aqueduct crossing 7.Electrical system crossing 8.Other utilities crossing.	1. Operating pressure (bar) 2. Diameter (inch) 3. Wall thickness (mm) 4. Burial depth (meter) 5.Maximum available operating pressure (MAOP) (bar) 6. Specified Minimum Yield Strength (SMYS) (bar) 7. Year of construction 8. Kind o f metal joint PIG data 9. Index to identify imperfection severity (FRS). Imperfections significant for FRS> 0,9 10. Number of internal and external imperfections of the tube 11. Absence of metal in the imperfections of the tube.

Table III. Main factors leading to failure due to corrosion, a mechanical cause, and third parties causes .

Causes	Hydrogeological factors	Anthropogenic factors	Technical factors
Corrosion	1. – 4. (Bedrock) – 5.	None	5. – 9.
Mechanical	1. – 2. – 3. – 4. – 5.	None	1. – 2.
Third parties	1.	1. – 2. – 3. – 4.	2.

4. Data sources

Three databases have been implemented to collect data, one for each of the main causes of accidents: corrosion, third parties, mechanical failure. The databases includes records describing either accidents or non-accidents. As regards corrosion, data from a specific crude oil pipeline in Italy (MonteAlpi Taranto, Italy) have been taken into account. For the other two causes, data from the US Department Of Transport (DOT) have been used, (http://primis.phmsa.dot.gov). These databases are used as the training and testing sets to identify a relationship between "factors" and "failures".

5. Evaluation of failure occurrence

The main goal of risk assessment is to encourage the implementation of preventive measures by eliminating risk evaluation's subjectivity. The idea of this approach to assess failure occurrence is to find a relationship between boundary conditions of an existing pipeline and the boundary conditions recorded in sites were a previous failure took place.

Since the relationship between "factors" and "failures", when existing, is very complex to be modelled, a "black-box" approach has been adopted. Specifically, in this work an Artificial Neural Network (ANN) approach has been used. A three-layered ANN, with factors as input unit, the fact that a failure happened or not as output unit, and choosing an adequate number of hidden units (equal to the number of input units) have been implemented for each of the three causes of failure.

6. Preliminary results

A preliminary study has been performed on the third parties factors causing an accident. In this case, 128 significant accidents has been extracted from the DOT dabase and characterised by the factors described in table V. These accidents often occurred in pipeline with very short diameters (90% of them were less than 12'). So, this factor, that is the pipeline diameter, was not taken into account in this preliminary study since it strongly affects the results. Specifically the following factors have been taken into account:

- Average population density in an area surface of 1km^2, in the neighbourhood of the pipeline, coded as follows: 0 low population density (less than 50inh/km^2), 1 high population density (more than 500inh/km^2), linearly proportional with values between 0 and 1 for population densities between 50-500 inh/km^2.

- Land use, classified in three classes as: other, farmland grass, crops; woodland, bare ground, orthogonally coded as follows: 000,100, 010, 001.
- Crossing of roads, coded with 0 no crossing, 1 crossing
- Crossing of rivers, coded with 0 no crossing, 1 crossing.
- Crossing of railways, coded with 0 no crossing, 1 crossing.

The ANN training also requires a set of negative patterns, in this case pipeline locations were an accident did not happen. Since, as it is widely reckoned, the pipeline accident is an extremely rare event, this set was generated taking into account all the possible permutations, that is defining the five factors quoted above (coded according to seven numbers), with the average population density assuming the values of 0, 0.33, 0.66 or 1, resulting in 128 different patterns. It is important to underline that for the 128 positive cases, just 35 of them were unique, while the others are duplicated patterns.
An ANN with 7 input units, 1 output unit, and 20 hidden units has been so trained. Fig.1 shows the trend of the square mean error of the output unit per number of learning iteration. The learning process was stopped after 10000 backpropagation learning iterations (mean square error, mse, less than 6%). Figure 1 shows the mse as a function of the learning step.
The ANN was then tested, in this preliminary approach on all the possible 128 permutations, so that to put in evidence the patterns that are more sensible to the occurrence of an accident. Table IV shows the 6 patterns that have shown a significant (greater than 0.75) prediction of accident occurrence. From this table some preliminary considerations or rules may be inferred. For example that higher population density seems to be a safer factor for third parties accidents, that roads crossings seems to be highly related to these types of accidents.

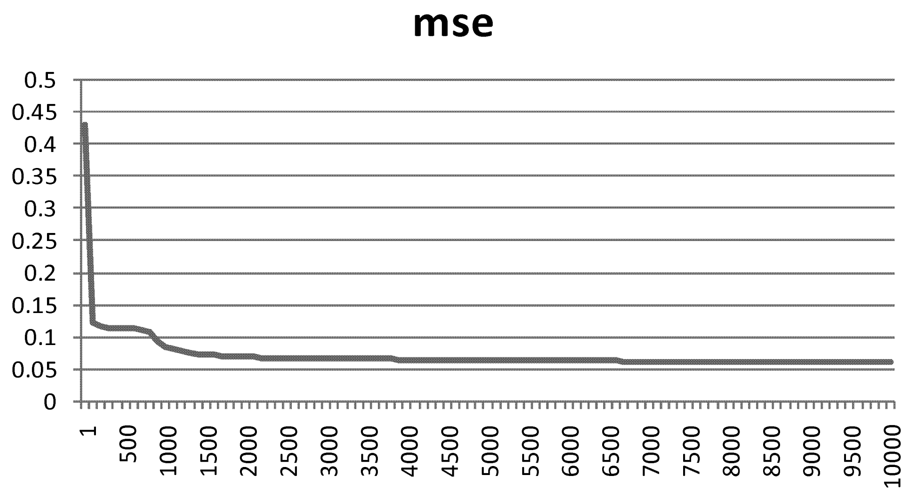

Figure 1. Mean square error as a function of the learning step during the ANN training on the set of 256 patterns (128 accidents, 128 no accidents).

7. Future Developments

In this preliminary results, the fundamental of the work to predict the occurrence of a pipeline accident has been exemplified. However, it is quite obvious that similar results

could have been obtained using more classical statistical approaches. However, the aim here is to use a methodology that can be easily adapted to peculiarities of a pipeline, adding for example historical data on accidents of a specific pipeline or of a set of National / regional pipelines. The ANN approach allows easily to customize the predictions of accident occurrence by properly modifying the training set.
In the next future research, the proposed statistical model and analysis will be applied to a specific case study located in the Monte Alpi -Taranto pipeline, in the south of Italy, adding also specific data of historical failures or accidents of that pipeline. This pipeline transports oil production from the Viggiano Oil Center to the Taranto refinery and it is 136 km long with a transportation capacity of more than 150,000 bopd (barrels of oil per day). Each sector of the pipeline network will be divided in segments of 50 meters of length, and for each of these segments the boundary variables related to territorial, technical and environmental conditions and other externalities will be retrieved through a complete geological study and several other sources of information.

Table IV. Significant (greater than 0.75) predictions of third parties accident occurrence by the ANN.

Population density	Farmland grass, crop	Woodland	Bare ground	Roads crossing	River crossing	Railway crossing	Prediction (1 acc., 0 no acc.)
0	0	0	0	0	0	0	0.893
0	1	0	0	0	0	0	0.999
0	0	1	0	0	0	0	0.989
0	0	0	0	1	0	0	0.903
0	1	0	0	1	0	0	0.958
1	0	0	0	1	0	0	0.763

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