

Transportation of Hazardous Materials via Pipeline: a Historical Overview

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The transportation of hazardous materials via pipelines is often considered a safer alternative to other transportation modalities such as railway, road and ship. However, pipelines often cross industrial and highly populated areas, so that their failure can pose a significant risk to the surrounding environment and the exposed population: the possible release of flammable and/or toxic materials in such areas can generate catastrophic events with very severe consequences. A number of accidents have actually occurred in the past years, and even when no deaths or injured are reported, significant damages to the surrounding environment often occur. This suggests that, given the extremely wide extension of the network worldwide, and the very high amounts of transported materials, a careful analysis is still required. In addition, the construction of pipelines also involves the contribution of expertise from a range of technical areas. As a consequence, the occurrence of accidents and the impact of their consequences, depend on the combination of a large number of parameters. In the present paper, an analysis of data relative to pipelines transporting hazardous materials has been carried out, and the influence of specific issues connected with their type and operation, has been assessed.

1. Introduction

Transportation of hazardous materials via pipeline is generally considered a safer alternative to other transportation methods, in particular railway and road. In a past analysis referred to oil transportation by different modalities (TRB, 2004), it was shown that, with the exception of tank and barge shipping, pipelines are the safest overall method in terms of failure rates, with the rate of fatalities, fires and explosions per ton-mile of oil transported being typically between half and less than 1/10 those of other methods.

Nonetheless, an accurate and detailed quantitative risk analysis of the transportation via pipelines is solicited for a number of reasons:

- a significant portion of the pipelines under operation is getting old, and the corresponding frequency of accident/release is expected to increase;
- pipelines often cross highly populated areas (often much denser than those crossed by rail and road transportation), so that even small releases can affect a large number of people;
- citizens' concern is continuously increasing.

When a quantitative analysis has to be carried out, the typical Quantitative Risk Analysis methodologies commonly used for rail and road transport (Bubbico et al., 2004a; Bubbico et al., 2004b) must be properly modified to take into account the different characteristics of all these transportation modalities (Boot, 2013):

- batch (rail/road) vs continuous (pipeline) mode;
- different impact of auxiliary and often manual activities (e.g. loading/unloading);
- impact of human reliability issues (e.g. tank driver);
- etc.

Due to the above considerations, in the recent years a number of studies were focused on the analysis of different aspects of the transport of hazardous materials via pipelines, as well as a number of additional duties

have been required by public authorities and regulatory bodies to pipeline operators, such as reporting either major accidents or near misses.

Based on data from 1970 to 1993, Golub et al. (1996) found out that most of the accidental releases from pipelines are caused by three event typologies: damages during excavation works, pipe material failure and corrosion, with 41 %, 28 % and 18 %, respectively. Damages during excavation were less frequent for deeper installations and the adoption of thicker pipes provided some benefit. In addition, the failure frequencies due to corrosion were estimated for different protection methods, i.e. with or without cathodic protection, and with or without insulation, obtaining the following figures: $8.7 \cdot 10^{-5}$ #/km-y, $3.7 \cdot 10^{-4}$ #/km-y, $1.1 \cdot 10^{-4}$ #/km-y, and $2.5 \cdot 10^{-4}$ #/km-y, respectively.

Kiefner et al. (2001), analysed data from 1985 until 1997 relative to gas and oil pipelines and found that the main accident causes were third parties activities (28.4 %), internal corrosion (12 %) and external corrosion (10 %). The trend with time showed that the number of accidents due to third parties activities gradually decreased probably thanks to more efficient control systems, such as the newly introduced Supervisory Control And Data Acquisition (SCADA) system, and to more severe regulations. Quantitatively, for pipe diameters up to 4", the failure rate associated to third parties activities was estimated $6.3 \cdot 10^{-5}$ #/km-y, while that for corrosion of pipes with insulation and cathodic protection was calculated as $9.7 \cdot 10^{-6}$ #/km-y.

Wang and Duncan (2014) analysed 35 serious accidents occurred between 1990 and 2009 involving natural gas pipelines, and found that: in 16 cases (46 %) a leak occurred with a frequency of $2.3 \cdot 10^{-5}$ #/km-y; a full bore rupture was observed in 6 cases (17 %) with a frequency of $8.7 \cdot 10^{-6}$ #/km-y, and in the remaining cases a release from valves, flanges, etc. was observed with $1.9 \cdot 10^{-5}$ #/km-y. Overall, the failure rate for natural gas pipelines increased from $3.5 \cdot 10^{-5}$ #/km-y in 1990 up to $9.5 \cdot 10^{-5}$ #/km-y in 2005, the main causes of failure being corrosion ($5.7 \cdot 10^{-6}$ #/km-y) and materials deterioration ($9.6 \cdot 10^{-6}$ #/km-y), altogether summing up 86 % of all cases.

In a report by US DOT published in 2010 (DOT, 2010), 493 cases occurred between 2005 and 2009 were analysed and classified as accidents involving dangerous liquids (305) and natural gas (188). For the first group, 30 % of the cases were caused by corrosion, 29 % by materials or welding failures and 23 % (71 cases) by damages during excavation works. Slightly different results were found for natural gas pipelines, where the causes were: 28 % corrosion, 23 % materials failure and 20 % excavation damages.

As far as European data are concerned, the European Gas Pipeline Incident Data Group regularly publishes reports collecting information on accidental releases from natural gas pipelines as provided by the most important European Companies. Based on 1309 accidents (EGIG, 2014), and on a total of $3.98 \cdot 10^6$ km-y, the overall accident frequency on the period 1970-2013 is 0.33 accidents every 1000 km, while it reduced to 0.16 #/(1000 km) between 2008 and 2013. With reference to the causes, in 35 % of the cases external events were responsible for the release, corrosion for 24 %, material failure 16 % and excavation damages 13 %. These values look rather different than the US ones.

Vianello and Maschio (2011) focused on the consequences of 1172 events involving natural gas pipelines across Europe from 1970 to 2007, with a frequency of $3.7 \cdot 10^{-4}$ #/km-y. A catastrophic rupture of the pipeline was observed in 13 % of the cases ($4.8 \cdot 10^{-5}$ #/km-y), and in 87 % of the cases the release was attributable to a hole or similar configuration ($3.2 \cdot 10^{-4}$ #/km-y). Following the release, a flash fire occurred in 50.4 % of the cases ($8 \cdot 10^{-6}$ #/km-y), a fireball or jet fire in 30 % ($4.8 \cdot 10^{-6}$ #/km-y), while no consequences and vapor cloud explosion (VCE) occurred with a probability of 14 % ($2.2 \cdot 10^{-6}$ #/km-y) and 5.6 % ($8.9 \cdot 10^{-7}$ #/km-y), respectively.

In a more recent analysis, also focused on the consequences possibly generated by a release of hazardous materials from pipelines (Bubbico et al., 2016), it was found that the type (pool fire, flash fire, etc.) and the frequency of occurrence of harmful consequences, markedly depended on the physical properties of the materials, and in particular, on its volatility. In 94 % of the cases involving low volatility liquids, no dangerous events were registered, while for compressed gases and pressure liquefied gases, a safe conclusion of the release was observed in only 38 % and 49 % of the cases, respectively; in addition, a catastrophic rupture is only possible for pressurized systems (pressure or liquefied gases, with 0.17 and 0.04 probability, respectively) while it was never observed for low volatility liquids. Similarly, in terms of dangerous phenomena, serious events occurred only with pressurized systems, while they were very rare for liquids (5 % for high volatility liquids).

A statistical analysis of historical data has also been carried out to assess the influence of land use on the accident frequency characterizing pipelines for the transportation of hazardous materials (Ramírez-Camacho et al., 2017). In accordance with previous studies (with the exception of DOT, 2010), it was found that the main cause of accidental release is associated with third parties activities (external events) with about 38 % of the cases, followed by corrosion (21 %) and mechanical failure (20 %); in addition, ageing was claimed to play a significant role in the two latter causes. It was concluded that all stakeholders (owners, users and companies working in the surrounding area) must be involved to increase the level of safety of this kind of transportation.

2. Types of pipelines

A range of characteristics can be associated to pipelines, depending on a number of issues: the transported material, the location and type of origin and destination (e.g. off-shore or on-shore network, from source to process plants or from process plants to marketplace), the location of installation. Considering the most commonly transported materials, i.e. natural gas and crude oil, a typical classification of pipelines is described below:

- flowlines connecting individual oil or gas wells to initial storage or processing facilities within the field;
- gathering lines connecting field facilities to the main long-distance networks, the transmission line (see below);
- transmission lines (longer and with larger diameters than the previous types) conveying oil to processing refineries and natural gas generally to urban distribution companies;
- for natural gas, the distribution network (composed of smaller diameter pipelines) conveying the product to commercial, residential or industrial final users;
- crude oil stops at refineries, while the processed petroleum products are subsequently transferred via the products pipeline system;
- of course, besides compressed natural gas, crude oil, and its processed liquids (products), many other substances can be transported via pipeline: LNG, ammonia, and so on; the corresponding pipelines are generically classified as "other".

Oil flowlines generally travel short distances (from less than a km to a few kilometers), have small diameters (2" to 12") and operate at relatively low pressures, typically below 7 barg. They usually end in tank farms, often including a three-phase separator (to separate oil, gas and water), and for this reason they are often defined as multiphase lines. In some cases, for crudes containing large amounts of salts or oils too viscous at low temperature, desalting or heating facilities are needed.

Similarly to oil flowlines, gas flowlines transport gas from individual wells to processing facilities, to remove entrained unwanted materials such as water, acid gases, liquid hydrocarbons, hydrogen sulphide or carbon dioxide, which might also induce corrosion and other problems in the transportation lines and associated equipment. The length of individual flowlines varies depending on the capacity of the producing well: normally from less than a mile to a few miles, with diameters 2"-4". The operating pressures can be higher than those for oil flowlines, up to about 20 barg.

The gathering lines convey oil from field-processing and storage facilities to larger storage tanks, from which they are subsequently pumped into the long-distance main transmission line. Their diameter varies depending on the flow rate of crude, on pipeline length and other factors, while the operating pressure is normally higher than that of field flowlines. They are usually owned by the same pipeline company that manages the transmission line.

Oil transmission lines move oil from large storage facilities to refineries or other storage terminals, with a wide variety of pipe sizes. Since they also cover quite long distances (several hundred miles, sometimes also crossing international borders), a number of pumping stations is required along the pipeline, to maintain the pressure and balance out friction losses, changes in elevation and other pressure losses. They are usually operated at higher pressures than the previous types and they require a complex and sophisticated monitoring and control system.

Gas transmission lines also cover long distances with diameters up to 60" and usually operate at higher pressures than crude oil transmission lines, with compressors properly spaced along the line. As with oil lines, they are made of steel pipes and they are often buried below ground, with an external coating to protect them against corrosion. In the case of natural gas, for land transportation and long distances, the vapor phase transportation is preferred, whereas liquefied natural gas (LNG) is transported via transmission lines on shorter distances: in fact, even if liquid phase transportation would be advantageous in terms of pipe size because of the higher density, considerable problems of insulation and the need for cooling stations along the line would be introduced for longer distances; in addition, due to the low temperatures, special stainless steels would be required to avoid embrittlement.

Gas distribution lines deliver natural gas to final customers and only refer to natural gas networks, representing last branch in the overall system. They operate at a lower pressure than the previous networks, but they cover most of the gas transportation total length. Pipe diameter ranges from 12 to 150 mm. They are usually owned by local distribution companies, starting from the so-called "citygate", i.e. the delivery point where the natural gas is transferred from a transmission pipeline to the local gas utility. Starting from this gate, two different subsystems are commonly identified:

- distribution main: a segment of pipeline installed to convey gas to individual service lines or other mains;
- gas service line: the piping installed between a main pipeline, or other supply source, and the metering system.

Products pipelines are used to transport refined petroleum liquids or other chemicals from refineries and chemical plants to storages, other processing plants or distribution facilities. The products include gasoline, jet fuel, ammonia and other liquids such as liquefied petroleum gases (LPG), consequently in many cases these lines operate at higher pressures than crude oil transmission lines. Common diameter size varies from 8" to 16", but also smaller and larger lines can be found. Products pipelines can also move several different products in the same line ("batched" products transport).

Other pipelines can transport a range of different hazardous materials including ammonia, chlorine, CO₂, hydrogen, etc. Large quantities of ammonia are transferred from production sites to other process plants for producing a number of derivatives, such as nitric acid, ammonium nitrate, urea and others. Ammonia is usually transported as a liquefied gas, either refrigerated or pressurized, and, in a significant number of cases, pipelines cross public roads or other populated areas.

Chlorine is also transported as a liquefied gas from the production site to plants for the manufacture of polyvinyl chloride, polyurethane and polycarbonate plastics; however, differently from ammonia, in most of the cases, transportation takes place within the same company premises or to different companies located in the same industrial area. Only in few cases the pipeline is allowed to cross public areas roads.

3. Data Analysis

The information adopted for the analysis have been gathered from a number of public databases.

The Pipeline and Hazardous Materials Safety Administration (PHMSA) of the US Department of Transportation (DOT), is in charge for research, development and control activities related with a total of about 3106 km of pipelines used for the transportation of hazardous materials. It is also responsible for shipping activities of hazardous materials by road, plane and ship, for a total of about 1 million daily shipping. The database is yearly updated, and the data adopted for the present analysis (both accidents and total pipeline length) span over the period 2010 to 2015.

All accidents involving the release of natural gas or oil from pipelines, independently of the amount released, must be reported in a standard form ("71002") in accordance with the regulation when one of the following applies:

- in the presence of fatalities or serious injuries requiring hospitalization;
- damages to properties exceeding \$ 50000, excluding released materials cost;
- emergency shut-down of the plant;
- any other event at operator's discretion.

The threshold of \$ 50000 has not been changed since 1985, and for this reason, the number of accidents reported has increased significantly over the years. In addition the "71002" form has been occasionally modified (in 1984, 2002 and 2010) and only in the most recent version more detailed information is included so that a meaningful statistical analysis is possible. That's the reason why the analysis starts from 2010.

The US National Transportation Safety Board (NTSB) is an independent investigation agency of the US Government in charge for the investigation of accidents connected with a wide range of transportation modalities (airplane, ship, railway, pipelines, etc.). The total number of reports is not very large, but the information reported is quite detailed, and therefore very useful for the analysis.

The Canadian Transportation Accident Investigation and Safety Board (TSB) is similar to NTSB, and investigates accidents occurred during transportation via ship, railway, oil and gas pipelines. Its Pipeline Occurrence Database System (PODS) is monthly updated and contains data starting from January 2004.

A total of about 900 accident reports have been collected, but only 669 provided enough information for carrying out a meaningful analysis. In Figure 1, the total number of the collected accidents is represented, per type of hazardous material class and per year, for the years from 2010 to 2015. It can be seen that, as far as natural gas is concerned, a constant or even slightly decreasing trend can be observed, while for crude oil and other oil products a more constant trend is found, but with a noticeable increase in the correspondence of year 2014. This latter increase is probably to be associated with a marked increase in the total length of operating pipelines (the "exposure", expressed as km-y) occurred between 2013 and 2014 (see Table 1): in just one year an increase of about 14000 km (corresponding to 6 %) characterizes the crude oil transportation network, while about 3 % is found for natural gas and oil products (namely, 3 % and 2.85 %, respectively).

Table 1: Total length of pipelines, per type of transported material class (years 2010-2015)

Length (km)	2010	2011	2012	2013	2014	2015
Oil pipelines	237416	240711	244478	244645	258333	264585
Products pipelines	139834	139528	139185	140740	144298	147324
Gas pipelines	2501166	2515970	2522003	2535003	2551334	2559848

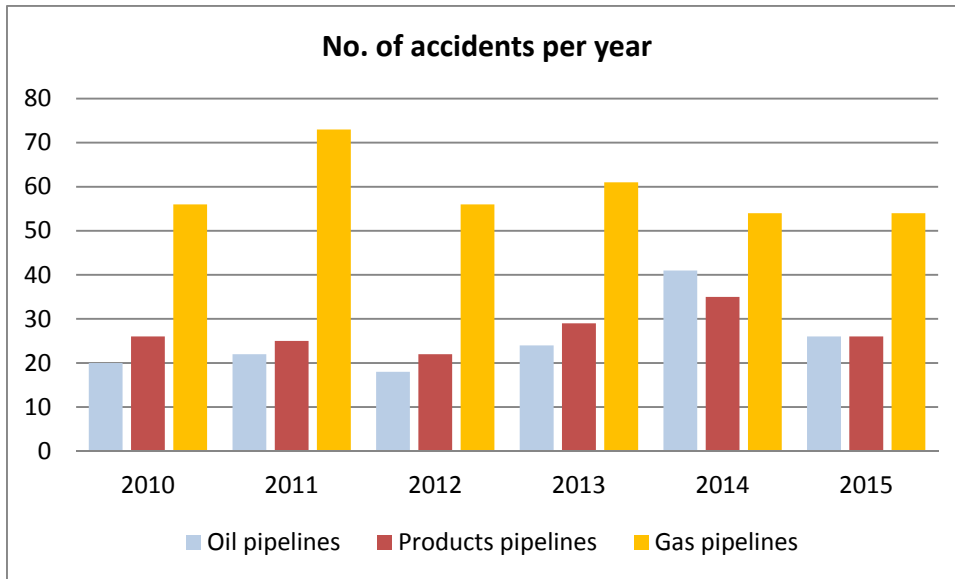


Figure 1: Accidents distribution per transported material type, from 2010 to 2015

The above considerations are better highlighted reporting the failure rate (accidents/km y), over the years (Table 2):

Table 2: Failure rate from 2010 to 2015, per type of transported material class

Failure rate (#/km-y)	2010	2011	2012	2013	2014	2015
Oil pipelines	$8.42 \cdot 10^{-5}$	$9.14 \cdot 10^{-5}$	$7.36 \cdot 10^{-5}$	$9.81 \cdot 10^{-5}$	$1.59 \cdot 10^{-4}$	$9.83 \cdot 10^{-5}$
Products pipelines	$1.86 \cdot 10^{-4}$	$1.79 \cdot 10^{-4}$	$1.58 \cdot 10^{-4}$	$2.06 \cdot 10^{-4}$	$2.43 \cdot 10^{-4}$	$1.76 \cdot 10^{-4}$
Gas pipelines	$2.24 \cdot 10^{-5}$	$2.90 \cdot 10^{-5}$	$2.22 \cdot 10^{-5}$	$2.41 \cdot 10^{-5}$	$2.12 \cdot 10^{-5}$	$2.11 \cdot 10^{-5}$

The overall average value for all pipeline types ($1.05 \cdot 10^{-4}$ #/km-y) is in line with those reported by similar analyses (Hill, 1992), where values of $7.4 \cdot 10^{-4}$ and $5.8 \cdot 10^{-4}$ #/km-y are reported, based on data from 1983 to 1991 by US-DOT and CONCAWE (European Oil Company Organization for Environment, Health and Safety), respectively.

With reference to the classification of substances adopted above, the analysis also addressed the main causes of release as a function of various parameters. In Table 3, under the title “other external cause”, events such as automobile impact, sabotage, domino effects, etc., are included; “natural force” damage means floodings, earthquakes, and so on; all other classes are supposed to be already self-explanatory. A more detailed analysis covering a wider range of materials and based on a different database can be found in Ramírez-Camacho et al. (2017).

The most frequent cause of pipe damage for crude oil is represented by corrosion (Table 3), with more than 50% of the cases, followed by damages during excavation activities and, with much smaller frequencies, all other causes.

Table 3: Release causes distribution per type of transported material class

Cause	Crude Oil		Products		Natural Gas	
	No.	%	No.	%	No.	%
Corrosion	76	54,7	37	27,6	17	10,9
Equipment failure	6	4,3	8	6,0	3	1,9
Excavation damage	26	18,7	33	24,6	76	48,7
Incorrect operation	6	4,3	6	4,5	10	6,4
Material failure	16	11,5	27	20,1	11	7,1
Natural force	3	2,2	8	6,0	5	3,2
Other incident cause	3	2,2	4	3,0	11	7,1
Other external cause	3	2,2	11	8,2	23	14,7

The large incidence of corrosion effects is compatible with the pipeline characteristics, since in almost all cases carbon steel was used for pipe manufacturing and in about 30 % of the cases no protection means were adopted during pipeline operation; in 23 and 25 % of the cases insulation or cathodic protection were present, and only in the remaining 22 % a full protection method was implemented. Similar results are also obtained for oil products: in about 90 % of the cases, carbon steel was used as pipe material and in 53 % of those cases, no kind of corrosion protection or just simple insulation was used. Excavation damages become the first cause of release for natural gas pipelines, with other outside forces being the second one, and a relatively more homogeneous distribution is found for other oil products (with “corrosion”, “excavation damage” and “equipment failures” representing more than 90 % of the cases). These results are in good agreement with previous studies (Hansler *et al.*, 2011; Ramírez-Camacho *et al.*, 2017). The reduced influence of corrosion in the case of natural gas is due to a combination of reasons: in a very limited number of cases carbon steel was adopted (about 7 %), replaced by stainless steel in more than 40 %; in addition, the frequent use of plastic materials for the pipes and the consequent absence of insulation, make the pipe more sensitive to mechanical damages.

4. Conclusions

In the paper, a historical analysis of recent data about accidents occurred during transportation of hazardous materials via pipeline is reported. It has been found that, despite the continuous increase in the total length of pipelines installed all over the world, a constant or even decreasing frequency of release is globally observed, especially for natural gas. The main causes of release, for each type of material transported, have also been identified and quantified in terms of relative occurrence: the main cause of release was found to be corrosion for crude oil (more than 50 %), and excavation damages for natural gas (around 49 %), while a more uniform distribution was observed for the generic class of oil products. The presented results might be of help in suggesting the adoption of proper prevention and/or protection actions to be implemented for a safer transportation of hazardous materials via pipelines.

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