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Review of failure trends in the US natural gas pipeline industry: An in-depth analysis of transmission and distribution system incidents

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A B S T R A C T

Natural gas (NG) transmission and distribution pipelines play an integral role in the United States (US) energy infrastructure. Various incidents over the past decades have caused growing concern as to the current condition of such pipelines in the US. Significant incidents were analyzed to understand the circumstances and causes to enable one to increase transmission and distribution line safety. Various data sets pertaining to significant US natural gas pipeline failures were analyzed in terms of transmission and distribution (main) pipelines. These categories were individually analyzed to develop an overall understanding of trends. While the report focuses on incidents over the '10 – '17 timeframe, additional analyses are included in the Appendix for two earlier time periods, '97 – '01 and '02 – '09. Only 'significant' incidents were included in the analysis, totaling 3000, and categorized in terms of: number of incidents, fatalities; pipe material; release type; ignition/explosion; location of loss; age of pipe; and cause of incident.

Four significant incidents within the distribution sets and three significant incidents within the transmission sets were further analyzed as case studies, seven in all. The case studies were developed to provide an in-depth analysis of events leading to failures, providing additional information gathered by the National Transportation Safety Board (NTSB), Pipeline and Hazardous Material Safety Administration (PHMSA), and additional local utility commissions. Finally, recommendations are made for further work in this area, including comparison of the findings of this analysis with on-going steps by the NG pipeline industry to reduce failures.

1. Introduction

In the United States, natural gas is used as a fuel, as well as a chemical feedstock. It is predicted that by 2040, 30 percent of the US energy consumption will be produced from natural gas, up from 28 percent in 2018 (PHMSA, 2018b; Pipeline Miles and Facilities, 2010+, 2018). Since 2010, natural gas consumption has increased by 12.5 percent to ~27.5 trillion cubic feet, compared with 23.3 trillion cubic feet in 2000 (EIA, 2018).

Coupled with an expanding economy, the industry is expected to employ an additional 1.8 million by 2025, including 500,000 manufacturing jobs and 320,000 chemical sector jobs. The industry is also expected to grow to an expected $533 billion by 2025, primarily due to the development of hydraulic fracturing (ET, 2017).

Natural gas primarily consists of methane in addition to other hydrocarbons and impurities. When burned, natural gas is considered a clean gas because it produces about half the carbon dioxide (CO_2) emissions as coal. Per Natural Gas Solutions, an advocate organization for natural gas, "Greater use of natural gas in power generation will also reduce nitrogen oxides (NOx), sulfur-dioxide SO_2, particle pollution (PM), acid gases, mercury (Hg) and non-Hg heavy metal emissions" (NGS, 2018). The increase in natural gas demand may also lead to an increase in CH_4 emissions due to production and transportation losses.

According to PHMSA, primary leaks within distribution and transmission lines occur from: corrosion, excavation damage, incorrect operation, material failure of pipe or weld, and natural force damage (PHMSA, Pipeline Incident 20 Year Trends, 2018a). Composed primarily of CH_4, natural gas is a much more potent greenhouse gas than CO_2 (Greenspon, 2015).

Pipeline failures lead to more than just environmental impacts. In many states, gas companies pass on the cost of lost gas to customers. Jackson et al. states, "a recent report estimated that US consumers paid more than $20 billion between 2000 and 2011 for lost and unaccounted for natural gas" (Jackson, 2014). Lost and unaccounted (LAU) gas, as defined by PHMSA, is the difference between the amount of gas purchased (e.g., what enters the gateway to the city) and the amount of gas sold (e.g., what is metered to customers). A study using PHMSA natural gas gathering, transmission and distribution data published in 2015 indicated that since 2010, nearly 12.9 billion cubic feet of natural gas escaped into the atmosphere – enough gas to heat more than 170,000 homes for a year (Thompson, 2015). Furthermore, failures in natural gas transmission and distribution pipelines over the past 10 years in the US caused an average of 6 fatalities, 30 injuries, and $85 MM in property damage annually.

Natural gas pipelines are generally divided into two primary categories, distribution and transmission. Distribution pipelines are

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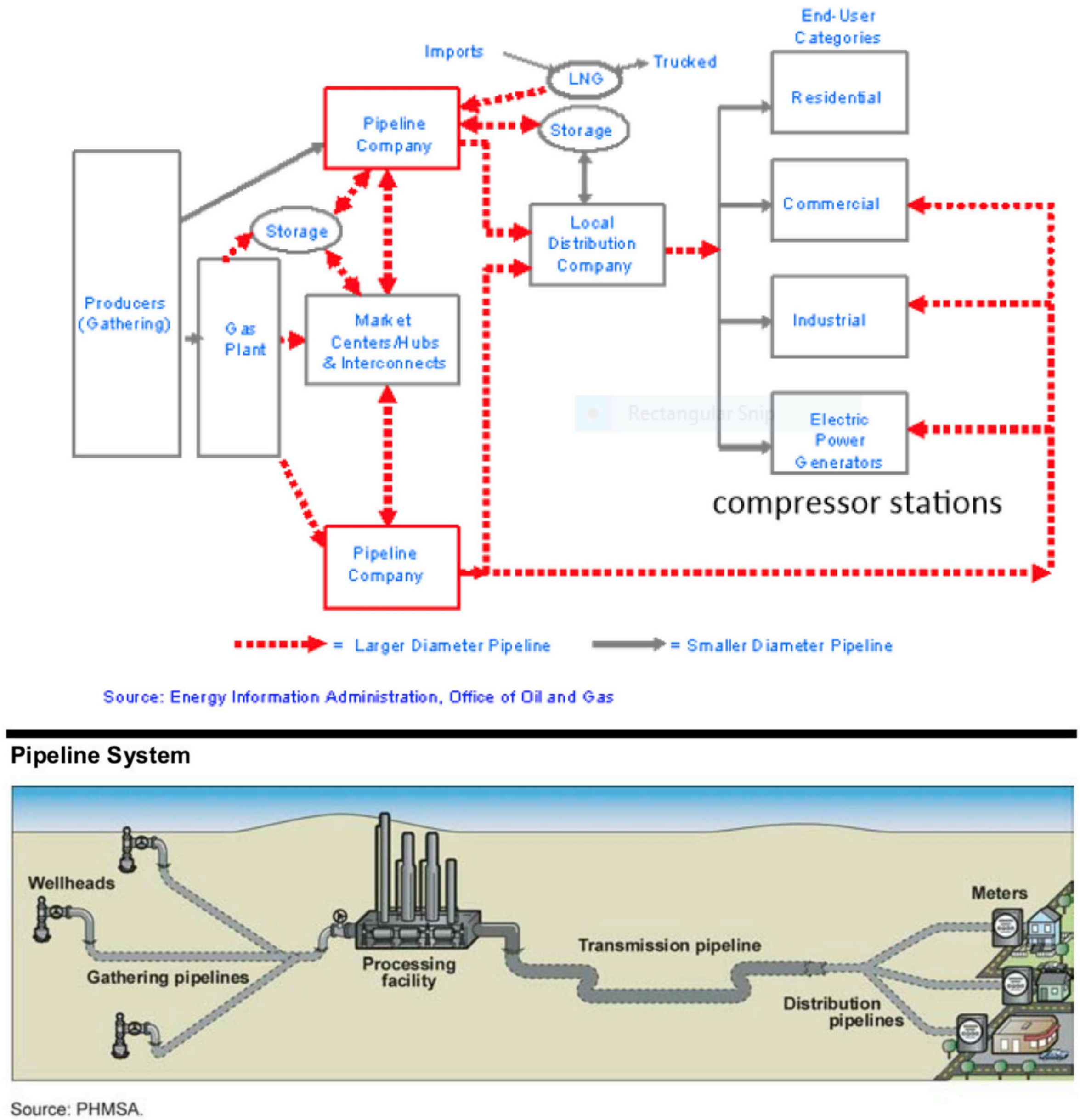

Fig. 1. Pipeline Infrastructure. [Top] A detailed graphic of transmission and distribution lines. Image obtained from http://www.eia.gov. [Bottom] Pipeline system depicting upstream, midstream, and downstream production (Government Accountability Office, 2012).

generally smaller diameter lines operating at lower pressures that deliver natural gas directly to local homes and businesses (American Gas Associaton, 2010). Transmission lines, on the other hand, are generally larger diameter lines operating at a higher pressure and transport natural gas between states, counties, cities and towns. Fig. 1 is a natural gas production and distribution schematic. Transmission lines are used to transport gas to local distribution companies. Once distribution companies obtain the gas, distribution lines are used to deliver gas to end users. End users include residential, commercial, industrial, and electric power generators.

A study performed by PHMSA in 2017 concluded that there are ~2.54 million miles of natural gas pipelines in the US. Distribution lines account for ~87% (~1.3 million miles of distribution mains and ~0.93 million miles of distribution service) and transmission lines account for 12% (0.30 million) of the total pipe, respectively (PHMSA, Pipeline Miles and Facilities, 2010+, 2018b). The remaining 1% of pipeline is composed of gas gathering lines, noting that there are also many additional miles of unregulated gas gathering lines.

Since the 1990s, there have been substantial reductions in miles of older cast iron (−38% to ~33,000 miles) and unprotected steel pipelines (−22% to ~66,000 miles). Conversely, there were increases in miles of protected steel (+8% to ~480,000 miles) and plastic (+150% to ~620,000 total miles) (Lamb, 2015). A campaign was introduced in 2011 by PHMSA to decrease the amount of cast iron and unprotected steel, to mitigate incidents from higher-risk pipeline infrastructure. The *Pipeline Safety, Regulatory Certainty, and Job Creation Act of 2011* called for the DOT to conduct state-by-state surveys on the progress of cast iron pipeline replacement (Pipeline Replacement Updates, 2018). The primary issue with cast iron is the use of bell and spigot joints, which are prone to leaks. Materials used to construct natural gas pipelines varied considerably over the previous 30 years, however the primary material used as of 2017 is plastic for distribution and steel for transmission lines.

In the current study, various data sets pertaining to significant US natural gas pipeline failures were analyzed. The purpose of this study is to provide an all-inclusive analysis of failures within the natural gas

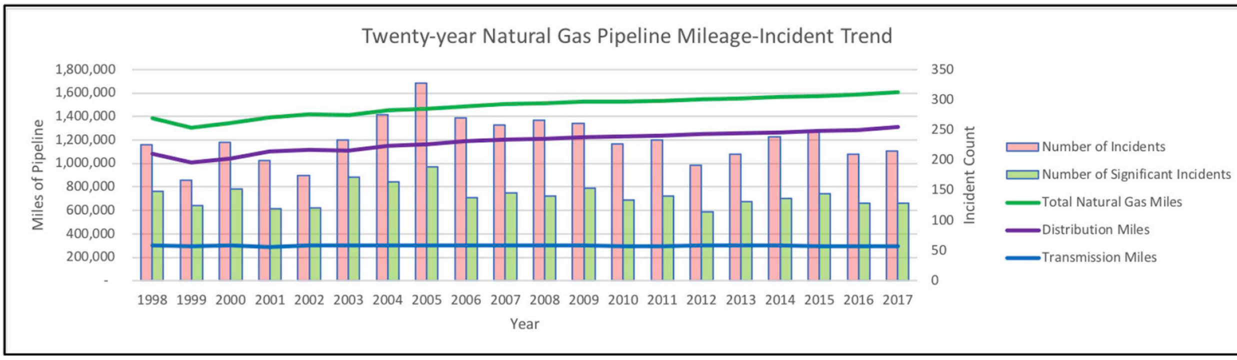

Fig. 2. Twenty-year trend indicating number of incidents and total miles of pipeline categories. Only distribution main miles were included in this analysis (PHMSA, Pipeline Incident 20 Year Trends, 2018a).

pipeline industry. Information presented builds on previous reports by updating old significant incident data, in addition to analyzing newly published information. This analysis was broken down into two separate and unique categories: transmission and distribution. Distribution data contains two subsets: main and service; mileage data was not provided for the distribution service subset prior to 2010. Four significant incidents within the distribution sets and three significant incidents within the transmission sets were further analyzed as case studies. The case studies were developed to provide an in-depth analysis of events leading to failures, constructed through information gathered by the NTSB, PHMSA, and additional local utility commissions.

Analysis of incidents has helped the Department of Transportation (DOT) develop trends and therefore implement new recommendations to help mitigate injuries, fatalities, and unintentional loss of natural gas. However, independent analysis of the data provided by PHMSA indicates concerning results in terms of incident prevention. Fig. 2 shows the relationship between miles of pipe and number of incidents graphically over the previous twenty years. Since 1998, the total number of incidents has remained relatively constant, recognizing that the total number of distribution miles increased slightly (16%) and miles of transmission lines remained relatively constant. Finally, significant incidents accounted for more than 50% of all incidents since 1998, indicating the risk and severity of a pipeline failure.

The DOT is committed to reducing the number of pipeline incidents. These measures include enforcement by PHMSA's Office of Pipeline Safety (OPS), which is the federal authority responsible for ensuring the safe, reliable, and environmentally sound operation of the US pipeline transportation system. OPS recommend that all members of the community, as well as stakeholders, to partake in its *Shared Responsibility* campaign. Through their website, PHMSA provides opportunities to become more involved in pipeline safety and disaster prevention by providing individuals with access to local emergency planning committees and the Common Ground Alliance (CGA).

CGA is a member-driven association of 1,700 individuals, organizations and sponsors in every facet of the underground utility industry. CGA is dedicated to preventing damage to underground utility infrastructure and protecting those who live and work near important assets through the shared responsibility of its stakeholders. This is done through information and analysis, education, and stakeholder engagement.

Data used in this report was obtained from a literature review from three noteworthy organizations: PHMSA, The American Petroleum Institute (API), and the Pipeline Research Council International (PRCI). An overview of each organization follows:

Pipeline and Hazardous Materials Safety Administration (PHMSA): PHMSA creates policies and standards for the transportation of energy and materials to protect people (PHMSA, 2017a). Since 1970, when an incident occurs within the natural gas transmission or distribution system, operators file a report with PHMSA that provide detailed aspects of the incident and pipeline. Report forms for transmission and distribution incidents contain similar categories, however the transmission form is utilized for gathering incident reports as well and therefore contains additional subcategories. As of 2014, the PHMSA Pipeline Incident Report Forms addresses: location, facility information, consequences, operating conditions, drug and alcohol testing information, apparent cause, and narrative description of the incident.

Such details are provided for a record of incidents, and so that information can be further studied to determine if there are trends for the causes of incidents. PHMSA has four databases: transmission, distribution, hazardous liquids, and LNG that range from 1970-Present. They also share their on-going research to develop technologies and methods to prevent incidents. Overall, PHMSA's website provided most of the information shared & analyzed within this report.

American Petroleum Institute (API): The API's mission is “to promote safety across the industry globally and to influence public policy in support of a strong, viable US oil and natural gas industry” (API, 2018). One major contribution that API has made for natural gas is their Recommended Practices (RPs). The RPs are documents that outline recommendations for operators, emergency response personnel, and communities regarding natural gas pipelines, and other oil and gas related matters. API is an excellent source of information for programs that are in place to improve the safety and performance of natural gas pipelines.

Pipeline Research Council International (PRCI): The PRCI is an organization that fosters collaboration, and research and development for energy pipelines. This source provides an extensive amount of information regarding research on mitigation technologies. The PRCI plans and develops these research projects through Technical Committees. “These committees are comprised of technical and operations experts from member companies” (PRCI, 2018). Topics studied by these committees include: Compressors and Pump Stations; Corrosion, Design; Materials and Construction; Integrity and Inspection; Measurement; Surveillance; Operations and Monitoring; and Underground Storage.

2. Discussion

Operators must notify the DOT of natural gas pipeline incidents that result in pipe failure. Incidents are defined as scenarios that result in any release of gas to the atmosphere. According to PHMSA, an event qualifies as an ‘incident’ if it results in at least one of the following:

- an event that involves a release of gas from a pipeline
- an event that results in an emergency shutdown of an underground natural gas storage facility
- an event that is significant in the judgement of the operator

PHMSA provides a 20-year database which contains information on more than 5,015 distribution and transmission pipeline incidents between 1997 and 2017.

To provide a sound analysis of failures, only significant incidents from the transmission and distribution (main) pipelines were analyzed in this work, so as not to bias the results with numerous minor releases. Studies have shown that the causes of significant incidents are not necessarily the same as those for minor incidents. Significant incidents are identified in this study as those including a fatality or injury requiring in-patient hospitalization or $50,000 or more in direct total costs measured in 1984 dollars (PHMSA, 2017a,b,c). The PHMSA dataset is over three distinct time periods: *1997–2001*; *2002–2009*; *2010-Present*. Process safety incidents such as these, result from the unintended release of natural gas. Thus, not all incidents resulted in personal injuries. Injuries and cost impacts were chosen to categorize the seriousness/magnitude of an incident, with the subsequent analysis addressing the causes and prevention/mitigation. Environmental impact is also a consideration, but difficult to measure quantitatively. Thus, safety and economic impacts are not separated, with the desire to prevent them both.

Trends within each dataset were individually analyzed. Categories analyzed were: number of incidents; pipe material; release type; ignition and explosion; location of loss; age of pipe; incident and fatality count; and cause of incident. A series of plots were developed depicting these incident characteristics, without requiring any statistical analyses (e.g., running averages). While all three time periods were analyzed, the focus was on the most recent (*2010 – Present)* dataset, since learnings from earlier incidents likely resulted in pipeline replacements, enhanced operating procedures, etc. Significant incidents averaged ~135 annually over the past 10 years, whereas the 10-year average for total incidents was ~230 over this more recent timeframe – nearly twice as many. While only the most recent data sets are included in the discussion below, graphs pertaining to previous years noted above are included in the Appendix and, when appropriate, noted in the discussion.

2.1. Pipe material

Fig. 3 provides an analysis of the type of pipe material failing in distribution and transmission pipelines. For both distribution and transmission lines, *steel* accounted for more significant failures than any other material. The category *other* for both transmission and distribution lines reflects non-typical piping materials, including aluminum, cross-linked materials (i.e., copper-plastic connection), and undetermined material. *Figure's A.1 and A.2* in the Appendix provide further insight to material failure over the previous 20 years. Average miles of pipeline per incident were not reported prior to 2010.

2.1.1. Distribution lines

According to PHMSA, in 2017 the most abundant pipe material in the ground was plastic for distribution lines, which became prevalent in the early 1970's. Prior to plastic, steel pipelines were used extensively since the 1950's. Uncoated steel pipeline, also known as bare steel pipe, has been systematically taken out of service due to age and lack of protective coating. Lastly, cast and wrought iron piping were used from the early days of pipeline transportation through the 1940's and is regarded as extremely high-risk. Despite programs in place to remove cast and wrought iron piping such as the Pipeline Safety, Regulatory Certainty, and Job Creation Act of 2011, many of these pipelines still deliver natural gas to homes and businesses today (United States Department of Transportation, 2017). Additionally, PHMSA Pipeline Safety Update indicates that the probability of steel and iron pipeline failures increases substantially once the pipe is more than 60 years old due to age and obsolete technology.

The natural gas industry is in the process of replacing old distribution pipelines with new plastic pipe. The large number of plastic failures in the distribution set in Fig. 3 (29%) can be attributed to the increasing amount of plastic pipe in the ground. Currently, plastic pipelines account for 54% of total main distribution lines, whereas steel accounts for 40% (PHMSA, Pipeline Miles and Facilities, 2010+, 2018b). Steel main distribution lines have decreased from 45.2% in 2010 to 40.6% in 2017. PHMSA designates uncoated steel pipelines to be part of accelerated replacement programs due to its higher failure rates.

In 2017, cast/wrought iron pipe only accounted for 0.01% of total distribution miles, yet it accounted for ~7% of the total distribution failures, as depicted in Fig. 3. The high failure rate of cast/wrought influenced the DOT to require annual analysis of all such pipelines (Pipeline Replacement Updates, 2018). Forms of analysis include stiffness testing, pigging, and geographical analysis. Geographical analysis is performed to mitigate the chance for cast/wrought iron to fatigue under stress from earth movement.

It is important to understand the limitations of this data, as the data in Fig. 3 is not normalized to account for the varying miles of pipe material for both sets of data. To address this limitation, Fig. 4A and 4B were developed. Rather than normalizing the incidents by the miles of corresponding pipeline material, we chose to portray the reciprocal - miles of pipeline per incident. The average miles used were taken from the 2017 PHMSA data, recognizing the number marginally increases each year.

As expected, Fig. 4A indicates that steel and iron distribution lines have more incidents per mile of pipe – or the least miles per incident as depicted. Note that steel is about five times more likely to fail than plastic whereas cast/wrought iron and ductile iron are 716 and 46 times, respectively, more likely to fail than plastic distribution lines. As noted by PHMSA, the failure rate of cast and wrought iron is significantly greater than all other piping materials.

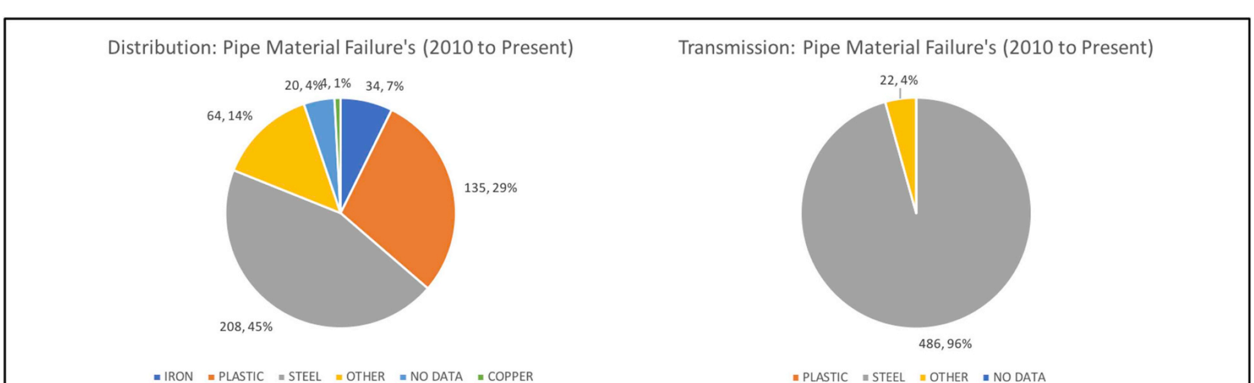

Fig. 3. Number of failures for each respective pipeline material of construction for 2010 to present (2017) (PHMSA, Pipeline Incident 20 Year Trends, 2018).

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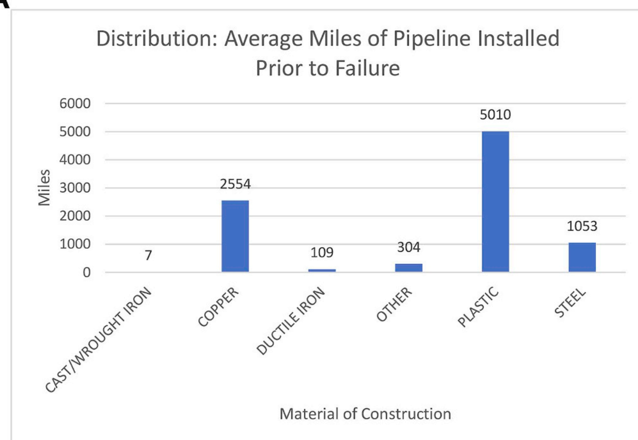


Fig. 4. A: Depicts the total miles of pipeline prior to failing in Distribution & Transmission pipelines from 2010 to 2017. B: illustrates that steel and iron pipelines have fewer miles per incident, or conversely more incidents per mile of pipe. The transmission lines in Fig 4B were not composed of Cast/Wrought Iron, Copper, Ducile Iron, or Plastic and therefore have no such data associated with them (PHMSA, Pipeline Incident 20 Year Trends, 2018a).

2.1.2. Transmission lines

According to PHMSA, in 2017 the most abundant transmission pipe material in the ground was steel. Based on the data presented in Fig. 3, *steel* accounted for more significant failures than any other material, which isn't surprising since most of the transmission lines are made of steel and thus per Fig. 4B fewer miles per leak than the more limited non-typical piping materials noted earlier.

2.2. Release type

Fig. 5 provides an analysis of the type of release from distribution and transmission incidents: in terms of leaks; ruptures; punctures; etc. There are certain characteristics that define each type release. A rupture is generally a longitudinal discontinuity caused by a superficial or near superficial manufacturing defect. Typically, during a *rupture*, the pipe “pulls apart” rather than cracking (Perez, 2016). A *leak* occurs when there is an unintentional escape of gas from the pipeline, such as loss due to corrosion. Lastly, a *puncture* occurs when there is total loss of the pipe wall extending over a small area (El-Sayed, 2018). The *other* category includes, but is not limited to, incidents such as a pipe being struck by a vehicle or a fracture occurring due to erosion. Although this data provides information on the release type, it does not reflect the severity of an event. For example, a *leak* may be considered relatively harmless if escaping gas remains below flammability limit thresholds. However, an incident that leads to a *rupture* can be extremely severe. An example is the San Bruno, CA incident that occurred in September 2010. The incident resulted in a *rupture* and explosion that was caused by an over pressured transmission line. The San Bruno, CA incident is further analyzed as a case study.

2.2.1. Distribution lines

Distribution data is primarily dominated by releases occurring from the *other* category (42%). Distribution lines tend to be in more densely populated areas, therefore giving rise to more opportunities for release types in the *other* category, where the pipe is impacted by excavation, etc. Of the four categories, ruptures accounted for the fewest failures (5%), with *punctures* and *leaks* at 25% and 28%, respectively. Figure A3 in the Appendix provides data on release types that occurred between 2002 and 2009. *Punctures* were not identified in this earlier timeframe. As with the present data, distribution incidents are dominated by *other* release types.

2.2.2. Transmission lines

Over half (55%) of the transmission releases are caused by *leaks*. According to the National Pipeline Mapping System (NPMS), transmission pipelines tend to be much longer than distribution lines (Department of Transportation, 2018). In addition to the length of transmission lines, they are typically made of steel, with large diameters and at higher operating pressures than distribution lines. Punctures are the least common (8%) reason for failure, with *ruptures* and *other*, 18% and 19%, respectively. Based on data presented in Figure A3 in the Appendix, for the years 2002–2009, *other* releases (44%) as well as *leaks* (34%) were prominent incident release types, with ruptures at 22% for transmission lines.

2.3. Ignition and explosion

Fig. 6 provides an analysis of events that resulted in ignition and/or explosion. Secondary ignitions were also recorded in this set of data. A secondary ignition, as defined by PHMSA, is a fire where the origin of the fire is unrelated to the gas system, such as electrical fires, arson, etc. It includes events where fire or explosion, not originating from a pipeline system failure or release, was the primary cause of the pipeline system failure or release. For example, a refinery fire that subsequently resulted in, but was not caused by, a gas transmission or gas gathering pipeline system failure or release (Pipeline and Hazardous Materials Safety Administration, 2014).

2.3.1. Distribution lines

Based on the ignition and explosion data in Figs. 6, 75% of all distribution incidents resulted in either an ignition and/or explosion. Figure A4 in the Appendix indicates trends for failures between 2002 and 2009. The trends with Fig. 6 are nearly identical.

2.3.2. Transmission lines

Results for the distribution and transmission data are vastly different for the ignition and explosion data, where only 17% of the transmission incidents resulted in either an ignition or explosion. Like Fig. 6, the *neither* category dominates the earlier data shown in Figure A4. However, while *explosions* and *ignition followed by explosion* were 7% and 0% in Fig. 6, respectively, the trend is switched in Figure A4.

2.4. Location of incident

Fig. 7 provides an analysis of the location of incidents upon failure. Potential locations for loss to occur include: *above ground*; *transition area* (moving from underground to above ground or vice versa); *underground*; *vessels*; and *offshore*.

2.4.1. Distribution lines

Distribution lines are not located offshore, and therefore failures of this type are not in the distribution data set. Distribution lines are primarily located *underground* which is where more than 50% of the incidents occur, while 41% occurred *above ground*. Figure A5 in the Appendix provides the results from 2002 to 2009. Note that this earlier data provides additional categorization in terms of under pavement, inside/under buildings, under water and in open ditches. *Above ground* and *underground* releases continue to dominate (34% and 29%, respectively), with additional detail regarding leaks *under pavement* (12%) and *inside/under buildings* (11%) combining for nearly 25%.

2.4.2. Transmission lines

Transmission lines are primarily located underground which is also where more than 50% of the incidents occur. About a quarter (26%) of the incidents occurred *offshore*, while 20% occurred *above ground*. Figure A5 in the Appendix for years 2002–2009 provides somewhat similar trends with 37% of incidents *under water*, 35% *underground,* and 16% *above ground*.

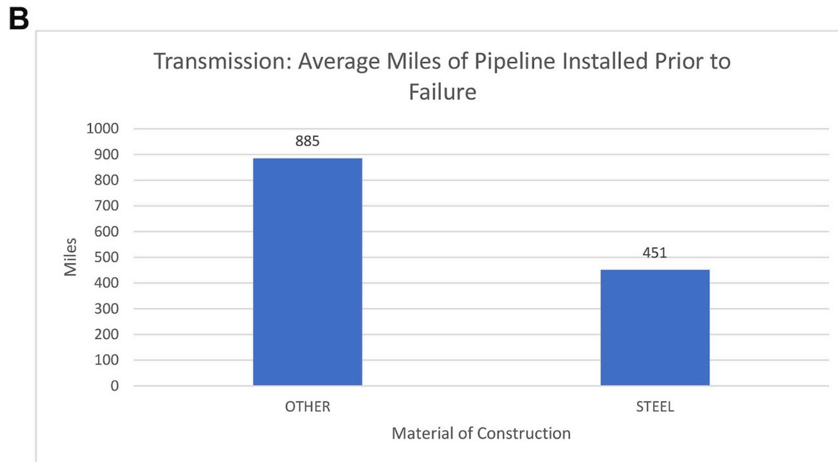


Fig. 4. (*continued*)

2.5. Age of pipeline

2.5.1. Distribution lines

Fig. 8 provides insight into the age of distribution pipe upon failure. According to the DOT, over the past 20 years there has been an initiative to replace all pipe older than 60 years (Pipeline Replacement Updates, 2018). This initiative has mitigated potential failure for old pipe. However, in accordance with Fig. 8, it can be noted that an abundance of failures occur prior to the 60-year period. Failures within this 60-year window occur for various reasons, with the primary being *other outside force damage* followed by *excavation damage*. Fig. 9 provides an assessment of failure analysis for the first five years after distribution pipe installation. This analysis includes both cause of failure, as well as material of the pipe involved, with two separate graphs, and includes both the earlier (2002–2009) and more recent (2010 – present) datasets. *Other outside force damage* and *excavation damage* were the top two reasons for failure during these two time periods. Plastic is the leading distribution material to fail. Recall that, as noted in Section 2.1, overall *steel* is the top material to fail, followed by *plastic*. *Copper* piping, shown in Fig. 9, accounted for 15 miles (0.01%) of total distribution (main) lines, and therefore was included in this analysis. There were no *copper* failures within 5 years of installation.

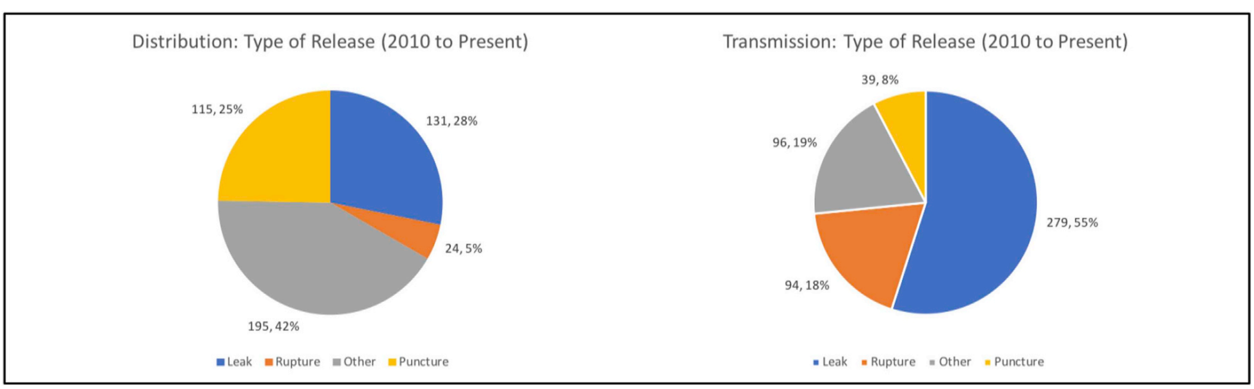


Fig. 5. Type of failure to occur upon release to atmosphere (2010 to present) (PHMSA, Pipeline Incident 20 Year Trends, 2018a).

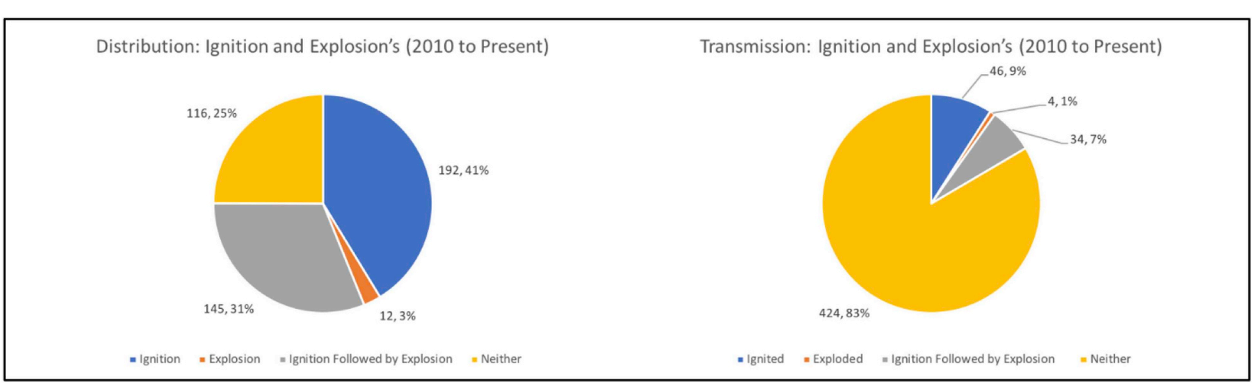


Fig. 6. Analysis of the number of incidents that experienced ignition, explosion, or both upon failure (PHMSA, Pipeline Incident 20 Year Trends, 2018a).

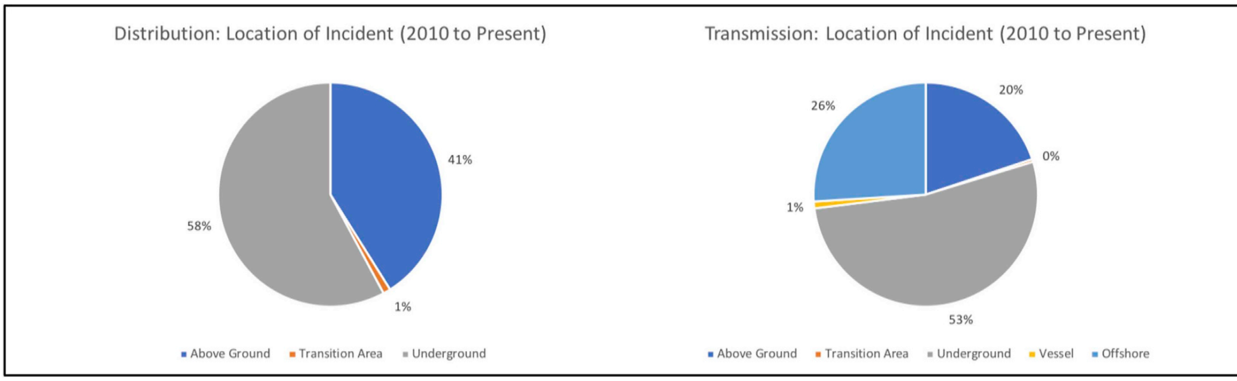


Fig. 7. Location of incident upon failure (2010 to present) (PHMSA, Pipeline Incident 20 Year Trends, 2018a).

Analysis for distribution failures within the first 15 years of pipe installation is available in the Appendix under Figure A6. Results are similar for the 15-year period, with *other outside force damage* being the top cause of incidents followed by *excavation damage* and similar conclusions regarding pipe materials. Additionally, there were no *copper* failures within 15 years of installation.

2.5.2. Transmission lines

Fig. 10 provides insight into the age of transmission pipe upon failure. Similar to the distribution data, the majority of the transmission failures are within the 60-year window, but with a clear peak at 35–45 years old. Transmission failures were primarily associated with steel pipe over the past 20 years. Due to transmission lines being composed primarily of steel (~94%), transmission data was not further broken down into five-year material failure categories.

2.6. Incident and Fatality Analysis

2.6.1. Distribution lines

Fig. 11 is a two-axis graph that relates the cause of distribution incidents with the cost and the number of fatalities. The highest cost associated failures were *excavation damage* (shown by the bar), which had nearly $85 MM in losses associated with it. *Other outside force* damage was the leading cause of fatalities, with the *other* incident cause second. According to the information reviewed in Section 2.5, *other outside force* incidents involve individuals who are not aware of the potential for pipeline failure. For instance, these incidents occurred due to damage by car, truck or other motorized vehicle/equipment not engaged in excavation. The high fatality rate associated with this data may be attributed to the inability for individuals to recognize the risk of their actions near a natural gas pipeline. Figure A7 in the Appendix provides analysis for incidents occurring between 2002 and 2009. The leading incident cost for distribution lines was *natural force damage* due to Hurricane Katrina, an extremely destructive category 5 hurricane, which occurred in August of 2005. Meanwhile, the leading cause of fatalities was *other outside force damage* and *excavation damage*.

2.6.2. Transmission lines

Fig. 12 is a two-axis graph that provides similar insight as Fig. 11, however for transmission data rather than distribution data. Note the magnitude of change on each axis as opposed to the distribution data – higher cost associated with larger high pressure transmission lines, whereas there are more incidents associated with the more plentiful distribution lines. The cause associated with the highest cost is *material and/or weld failure*, adding up to nearly $6.3 billion, far above the other categories. In addition, this incident cause also accounted for the leading number of fatalities. All of the fatalities associated with this cause of incident came from the same San Bruno, CA event (2010), which claimed eight lives and attributed to a loss of nearly $560 MM. Based on Figure A8 in the Appendix between 2002 and 2009, the leading incident cost for transmission lines was *natural force damage* due to Hurricane Katrina, and the leading fatality cause for transmission data was *excavation damage*.

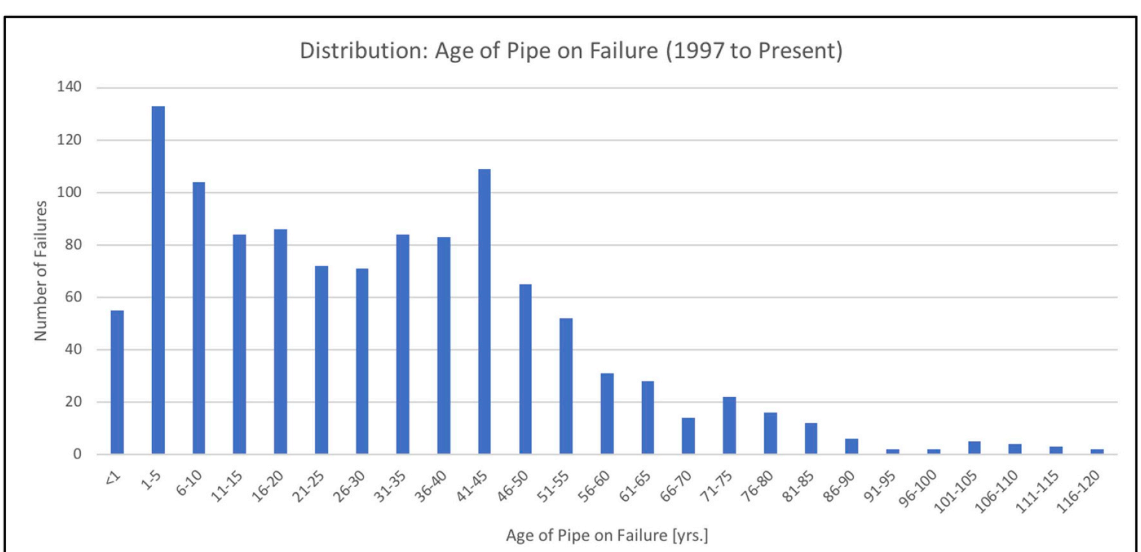


Fig. 8. Age of distribution pipeline network on date of incident (PHMSA, Pipeline Incident 20 Year Trends, 2018a).

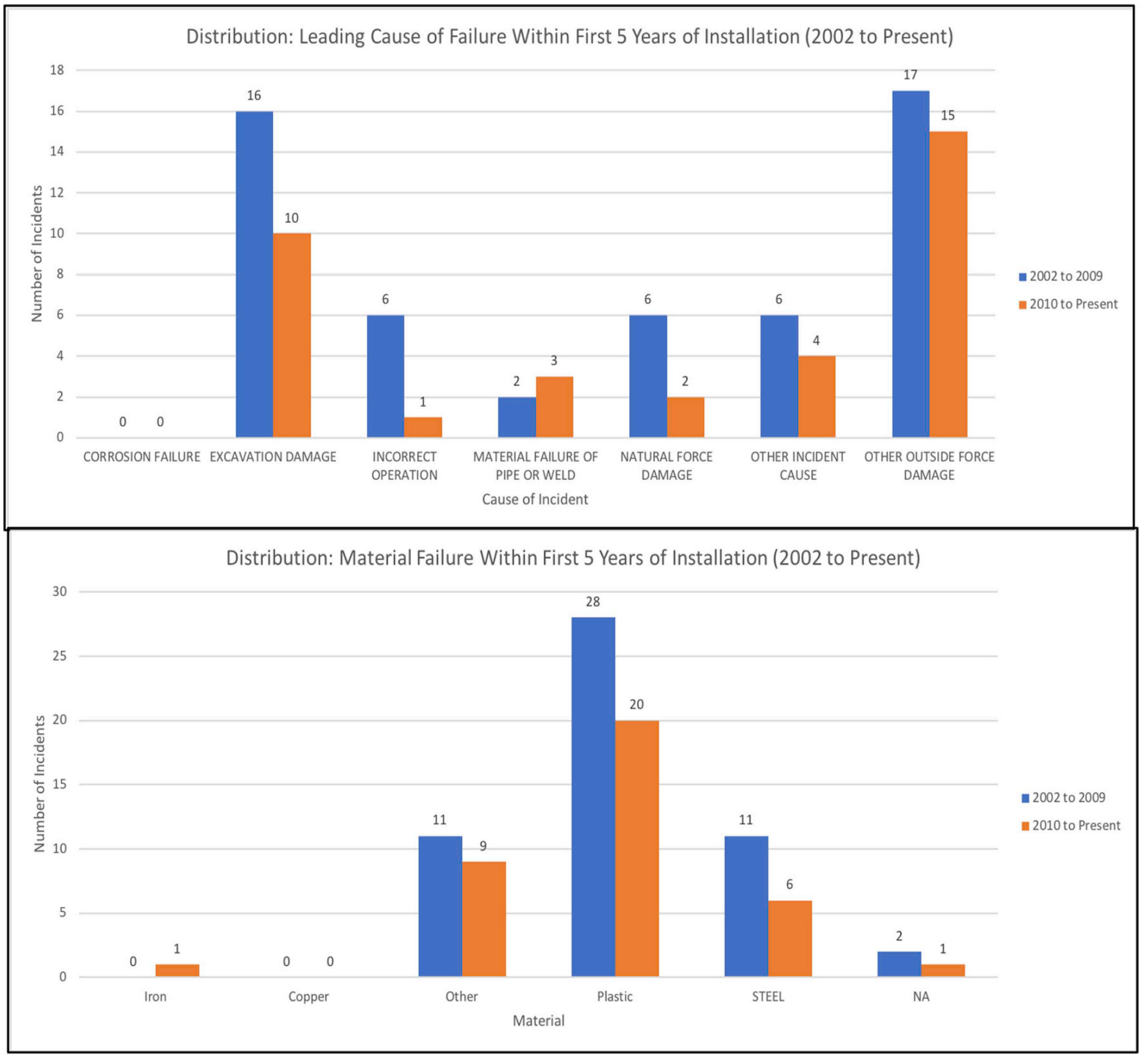


Figure 9. [TOP] Bar graph depicting the leading causes of failure when a pipe fails within the first five years of it being installed. [Bottom] Bar graph depicting the number of failures involved with specific material within the first five years of pipe installation (PHMSA, Pipeline Incident 20 Year Trends, 2018a). There were no failures for copper within five years of installation.

2.7. Cause of Incidents

Fig. 13 provides an analysis of the cause of incident failures. There are seven categories of causes per the PHMSA data for distribution lines, with an 8th cause added for transmission lines – *equipment failure*.

2.7.1. Distribution lines

Distribution failure is dominated by *other outside force damage* (34%) with *excavation damage* a close second (28%). *Other outside force damage* considers incidents that occur from damage by a car, truck, or other motorized vehicle/equipment not engaged in excavation. It also accounts for industrial, man-made, or other fires/explosions as primary causes of incidents. High ignition and explosion rates within distribution lines identified in Section 2.3 may be caused by these other outside force factors in part because of their location in more populated areas. Figure A9 in the Appendix provides additional insight into trends of distribution failures between 2002 and 2009. Similar to the recent timeframe, the primary cause for these failures was *other outside forces* between 2002 and 2009, with *other outside forces* and *excavation damage* again accounting for nearly 2/3's of incidents (62%).

2.7.2. Transmission lines

The cause of failure in transmission lines is primarily *corrosion*, with 31% of the failures, followed by *material failure of pipe or weld* and *equipment failure*, both being 17%. *Equipment failure* accounts for incidents where relief/control equipment does not properly operate or threaded/non-threaded connection failures occur. In Section 2.2, leaks were the primary release type found in transmission lines. The high corrosion failure rate is consistent with this. The trend is similar to that in Figure A9 in the Appendix where the primary cause of transmission failure was *corrosion* (26%) between 2002 and 2009, with *natural forces* and *material and/or weld failure* next at 16%.

For comparison, since 1982 a group of European gas transmission pipeline operators (now 17 in total) have been sharing and compiling incident data. Recognizing that their incident categorization is somewhat different from PHMSA, for the period 2007–2016 (somewhat similar to Fig. 13), the leading cause of incidents was 'external interference' at 28%, followed closely by corrosion at 25% (EGIG, 2018).

3. Case Studies

3.1. Distribution case studies

A - March 12th, 2014 New York, NY. On March 12, 2014 two adjacent multiuse five-story buildings were destroyed by a natural gas-fueled explosion and resulting fire (National Transportation Safety

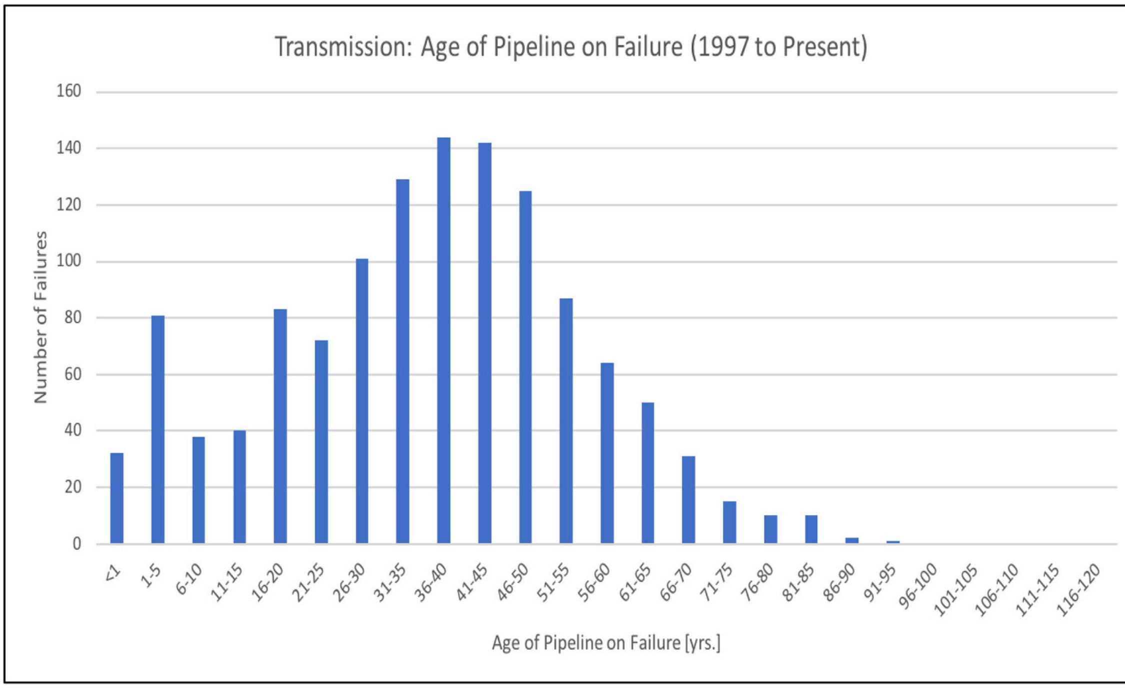


Fig. 10. Transmission age of pipeline network on date of incident (PHMSA, Pipeline Incident 20 Year Trends, 2018a).

Board, 2015). The distribution line was operated by Consolidated Edison Company of New York, Inc. (Con Edison). The explosion left eight people dead, 48 injured, and caused nearly $3 MM in damages (PHMSA, Pipeline Incident 20 Year Trends, 2018). Accordingly, "the explosion would have never happened had two Consolidated Edison pipes been welded together properly" (McGeehan, 2015).

An investigation by the NTSB determined two probable causes of the accident. The first was the failure of a defective fusion joint at the service tee, installed by Con Edison in 2011, that allowed natural gas to leak from the gas main and migrate into the building where it ignited. Second, a breach in the sewer line that went unrepaired by the New York Department of Environmental Protection, since at least 2006. This allowed groundwater and soil to flow into the sewer, resulting in a loss of support for the gas main, which caused the line to sag and overstressed the defective fusion joint (National Transportation Safety Board, 2015).

At 9:06 a.m. on the day of the incident, a resident of a nearby building called Con Edison to report a natural gas odor. However, miscommunication between the dispatcher and a NYFD (New York Fire Department) representative resulted in the gas leak not being reported to emergency responders. Subsequently, at 9:30 a.m. the pipe ruptured.

As a result of the incident, safety recommendations were made by the NTSB, to the New York State Public Service Commission, the City of New York, and Con Edison (National Transportation Safety Board, 2015). The NTSB suggested that the City of New York ensure a written program or procedure be in place to ensure the integrity of sewer lines, and that they are properly repaired. Con Edison received a series of recommendations to revise the plastic pipe welding fusion procedure, provide clear written guidance to the Gas Emergency Response Center staff, and extend the gas main isolation valve installation program.

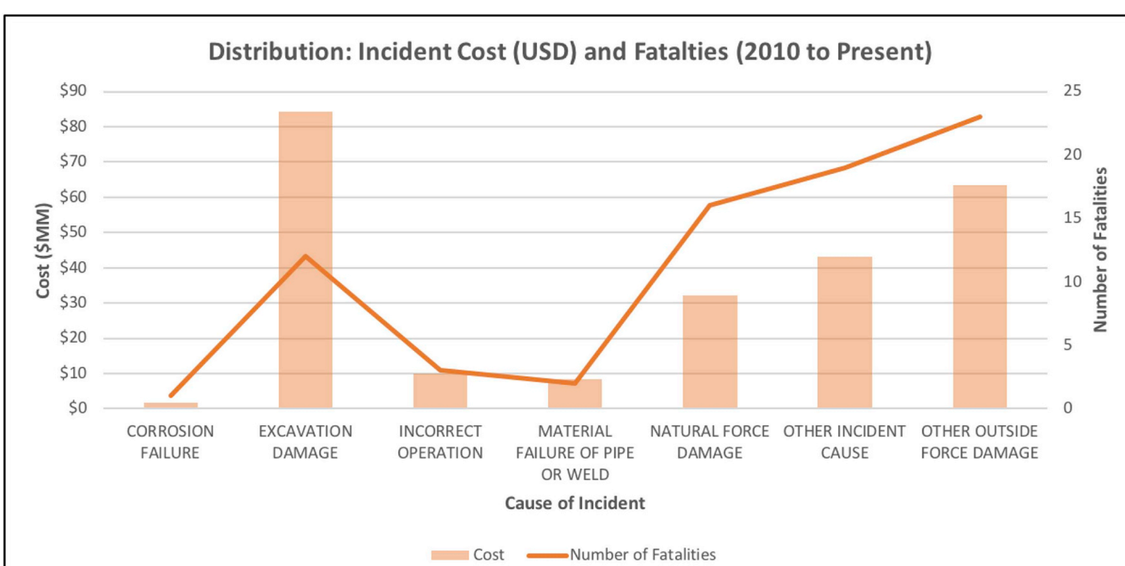


Fig. 11. Distribution incident cost (USD) and fatalities (2010 to Present) (PHMSA, Pipeline Incident 20 Year Trends, 2018a).

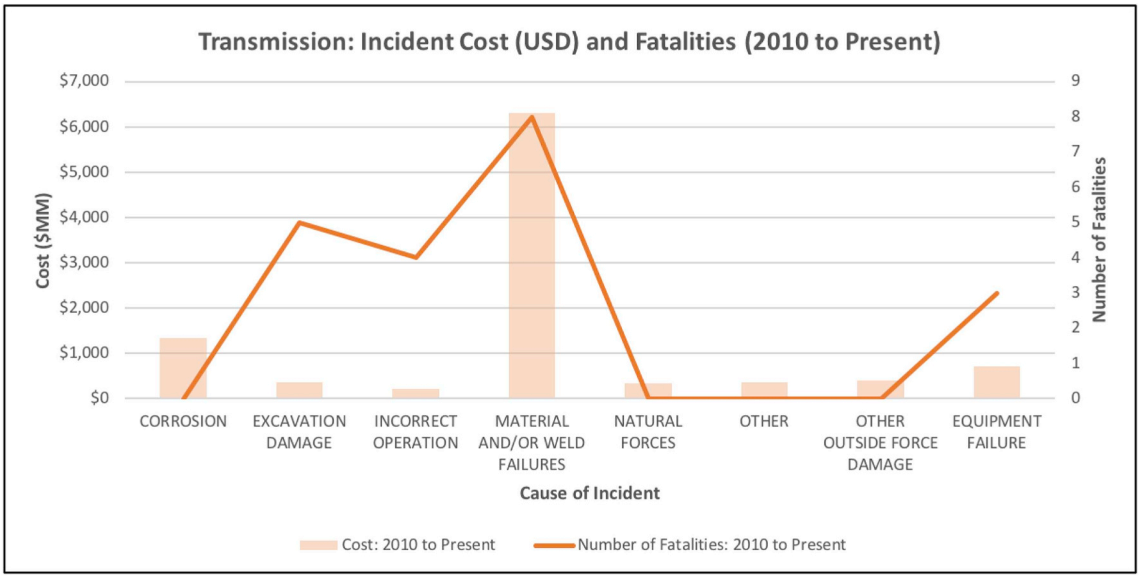


Fig. 12. Transmission incident cost (USD) and fatalities (2010 to Present) (PHMSA, Pipeline Incident 20 Year Trends, 2018).

Finally, the New York State Public Service Commission was advised to revise its gas utility operator program.

B - February 23rd, 2018, Dallas, TX. On February 23rd, 2018, about 6:38 a.m., a natural gas-fueled explosion occurred at a newly renovated single-story residence in Dallas, Texas (National Transportation Safety Board, 2018). The explosion occurred following two incidents that occurred the preceding two days. According to a preliminary NTSB report, the initial explosion occurred on February 21, 2018, at 5:49 a.m. at 3527 Durango Drive; about 415 feet from the eventual Espanola Drive explosion (National Transportation Safety Board, 2018). The first incident was a fire resulting from an explosion due to a faulty HVAC unit. The second incident, a structural fire, occurred on February 22nd, 2018, at about 10:21 a.m., at 3515 Durango Drive; resulting from gas stove flames that were “red and out of control” (National Transportation Safety Board, 2018). This incident was less than 310 feet from the Espanola Drive house explosion (National Transportation Safety Board, 2018).

In accordance with federal investigators, “Atmos Energy had been aware of gas leaks in a northwest Dallas neighborhood for more than seven weeks before the explosion” (Branham, 2018). Multiple leaks had been previously identified throughout the neighborhood. On January 1st, 2018, odors were reported highlighting the leaks within the community. The NTSB preliminary report indicates that Atmos had performed various repair work prior to and during the days these three incidents occurred (National Transportation Safety Board, 2018). Atmos crews were investigating and repairing leaks directly behind the house the night before the blast, in response to an explosion and subsequent fire on [Durango Drive] (Branham, 2018).

In response to the third incident, mandatory evacuations were issued to residents living in homes three blocks to the north and three blocks to the south, which included Espanola Drive and Durango Drive (Brujin et al., 2018). Over the course of the evacuations, Atmos Energy replaced 2.5 miles of pipeline throughout the area, including natural gas mains and service lines. A 3-person team from the NTSB is investigating the explosion further (Zehl and Associates, 2018).

C - February 9th, 2011, Allentown, PA. A thunderous gas explosion devastated a rowhouse neighborhood, killing five people (Associated Press, 2011). On February 9th, 2011, a cast-iron main installed in 1928 beneath Allen Street in Allentown, PA cracked, resulting in an explosion (McEvoy, 2013). The source of the natural gas that led to the explosion was a 12-inch cast-iron main with a circumferential crack (Metro, 2011). A 16-month investigation performed by the utility commission found that a UGI work order from December 1979 recommended the pipe for replacement, but that never happened (McEvoy, 2013).

In addition to the December 1979 work order, UGI was reminded in August of 1991 by the NTSB that all operators of cast iron pipelines implement a program to identify and replace cast iron pipelines that may threaten public safety. According to PHMSA, “at the end of 2009, plastic and steel pipe made up approximately 97% of mileage of natural gas distribution pipelines in the US. The remaining 3% is primarily iron

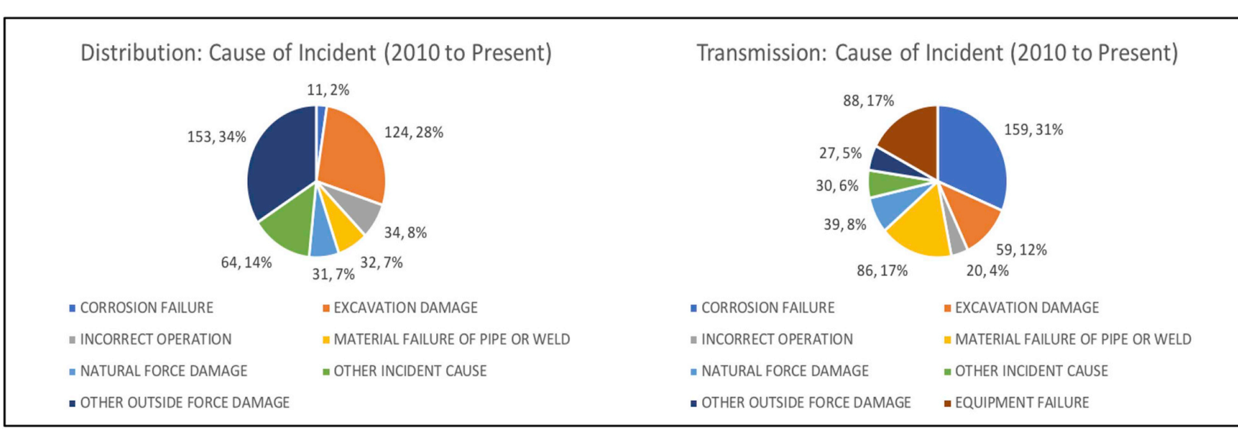


Fig. 13. Distribution and transmission cause of incident (2010 to present) (PHMSA, Pipeline Incident 20 Year Trends, 2018a).

Fig. 14. Home on fire following natural gas distribution pipeline leak in Boston, September 13, 2018 (New York Times, 2018):

pipe, either cast, wrought or ductile iron. The leaking pipeline in Allentown is made of cast iron and was installed in 1928." (PHMSA, UGI Utilities Pipeline Leak in Allentown, PA, 2017). After excavation of the pipe, it was discovered external corrosion led to 80% wall loss of the main (Metro, 2011).

The safety report conducted by the Pennsylvania Public Utility Commission indicated that no one was prepared for a major incident like Allentown or San Bruno (Metro, 2011). Specifically, there were a chain of events that led to the explosion in Allentown, and these events could have been prevented had proper cautionary measures been taken. The result of the 2011 incident in Allentown, PA indicates the importance of following NTSB recommendations.

D - September 13th, 2018, Boston, Massachusetts. On September 13, 2018, a natural gas distribution pipeline ruptured 25 miles north of Boston, which spurred dozens of explosions and fires, as shown in Fig. 14. This ultimately affected three communities nearby where fires were ignited in 60–80 homes. This resulted in one fatality, dozens of injuries and the evacuation of nearly 8,000 people from the surrounding area. In addition, nearly 18,000 homes and businesses were left stranded without power (CNBC News, 2018). Preliminary investigations claim the cause to be the over-pressurization of the gas lines. However, the complete incident investigation is yet to be completed by PHMSA and other authorities to identify the primary root cause(s). The gas pipelines are owned by Columbia Gas of Massachusetts (Lee & Soraghan, 2018).

3.2. Transmission case studies

A - September 9, 2010, San Bruno, CA - the most devastating pipeline accident in a decade.

At 6:11 p.m. on September 9, 2010 in San Bruno, CA, a 28-foot section of carbon steel pipe erupted from the ground. The section of pipe, owned and operated by Pacific Gas & Electric (PG&E), landed nearly 100 feet from the blast's epicenter (Repanich, 2011). The explosion led to eight deaths, 51 injuries, nearly 40 houses destroyed, and ~ $600 MM in damages (Wald, 2011). Almost immediately after the rupture occurred, escaping gas ignited, creating an inferno, as shown in Fig. 15. According to a report by the NTSB, the 30-inch diameter pipe had numerous flaws in its welds (National Transportation Safety Board, 2010). The section of pipe that failed, originally welded in 1956, did not meet generally accepted quality control and welding standards in effect.

The rupture was a result of over pressurization of the segment of pipe (Line 132) due to a series of issues within the PG&E Milpitas Terminal. An uninterruptible power supply had been undergoing maintenance at the facility when an open circuit resulted in a local control panel unexpectedly losing power. As a result, a series of valves were fully opened, and Line 132 was over pressurized. Monitor valves were in place to prevent over pressurization within the mains from occurring. However, the monitor valves were displayed as closed after a series of erroneous signals were sent to the supervisory control and data acquisition (SCADA) unit due to the resulting outage. Subsequently, the gas ignited and exploded following over pressurization of the line segment.

Fig. 15. Fire in San Bruno, CA following transmission line release, September 9, 2010 (San Francisco Chronicle, 2010):

According to the NTSB, "The investigation determined that the California Public Utilities Commission (CPUC), the pipeline safety regulator within the state of California, failed to detect the inadequacies in PG&E's integrity management program and that the PHMSA integrity management inspection protocols need improvement" (National Transportation Safety Board, 2010).

B - April 17th, 2015, Fresno, California. On April 17th, 2015, in Fresno, CA, an explosion occurred when a backhoe struck a 12-inch gas line (Eversley, 2015). The explosion killed one and injured 11 others, according to PHMSA. A report from the CPUC indicated the operator of the backhoe struck the buried gas pipeline while digging in the side of a hill. The report stated that there was no wrong doing by PG&E, whom own the gas pipeline (Benjamin, 2016).

The explosion ejected a portion of the pipe 34 feet from the blast's epicenter. The incident, caused by outside force damage, cost PG&E ~$2 MM in losses (California Public Utilities Commission, 2016). An investigation performed by the Safety and Enforcement Division (SED) of the CPUC indicated that a USA One Call 811 ticket was never requested by the County of Fresno Public Works. Every three years, PG&E sends businesses within 2,000 feet of PG&E owned gas transmission pipelines operating at pressures greater than 60 psig, including residents located in Fresno County, a notification of their proximity to a transmission pipeline (California Public Utilities Commission, 2016).

In conclusion, the CPUC determined that the Fresno County Public Works failed to properly survey the dig site prior to excavation. This incident could have been prevented had the Fresno Public Works called 811 to identify potential underground main lines. It was determined that PG&E had properly notified Fresno County of the pressurized piping main and was therefore not held liable for the incident.

C - February 14th, 2011, Carthage, Texas. On February 14, 2011, an explosion and fire occurred at the Gulf South Pipeline Company, LP (Gulf South) Carthage Junction Compressor Station in Panola County, Texas (Roberson, 2013). A check valve failure during system shutdown resulted in a station fire.

The section of pipe involved contained a 24-inch check valve. According to *Stress Engineering* in Houston, TX, the central assembly bolt in the check valve failed (Roberson, 2013). The failure resulted in an approximate 14-inch-long longitudinal rupture. Per the investigation, many factors contributed to the failure including: heat impingement in the area of small oxide inclusions at the site of the failure; partially open discharge valve due to parts of failed check valve; reverse rotation of a compressor; lube oil fire ignited escaping gas product; heat impingement from lube oil fire caused the 24-inch suction elbow to fail; Emergency Shutdown (ESD) system malfunctioned due to improper design (Roberson, 2013).

As a result, $35 MM in losses occurred due to surrounding damage from the explosion and loss of gas. According to PHMSA, the Carthage Junction incident resulted in a monetary loss just second to the *San Bruno, CA* explosion (largest since 2010).

4. Conclusions

The PHMSA database is a rich source of data on natural gas pipeline incidents over nearly two decades with significant data captured for each incident. There are various findings in each section of this report. Conclusions are based on the trends shown by the 13 graphs in the body of this report focused on the ‘10 – ’17 timeframe, supplemented by nine graphs in the Appendix for the earlier time periods. Key learnings follow by section:

4.1. Distribution lines

Pipe Material (Section 2.1):

- Plastic is the safest construction material and averages ~5,000 miles per failure
- Cast/wrought iron and ductile iron pipe are the highest risk materials, and are ~700 and ~50 times more likely to fail than plastic, respectively

Release Type (Section 2.2):

- Distribution lines are more likely to fail due to a vehicle or individual striking the pipe, or erosion

Ignition and/or Explosion (Section 2.3):

- Distribution lines are more likely to result in an *ignition and/or explosion*

Location of Incident (Section 2.4):

- These lines are typically on land and underground, where 58% of leaks occur

Age of Pipeline (Section 2.5):

- Other outside force damage followed by excavation damage are the primary reasons for early (< 5 years) distribution pipeline failures
- Plastic distribution pipe material has more failures within 5 years of installation than other materials, likely due to it being the most abundantly used material for new distribution pipelines

Incident and Fatality Analysis (Section 2.6):

- *Excavation damage* contributes the highest monetary loss in distribution failures followed by *other outside force damage*
- *Other outside force damage* is the primary cause of fatalities in distribution incidents

Cause of Incidents (Section 2.7):

- *Other outside force damage* and *excavation damage* are the two primary causes of failure in distribution incidents, accounting for +60% of incidents, with seven incident causes captured

4.2. Transmission lines

Pipe material (Section 2.1):

- Transmission pipelines are most commonly made of steel

Release Type (Section 2.2):

- Transmission lines are most likely to fail due to *leaks* (i.e., corrosion)

Ignition and/or Explosion (Section 2.3):

- Transmission lines are less likely to result in an *ignition and/or explosion* with 83% not igniting

Location of Incident (Section 2.4):

- The pipelines are typically *underground where 53% of leaks occur, with 26% offshore*

Age of Pipeline (Section 2.5):

- 94% of transmission pipelines are made of steel, with most leaks occurring on steel pipe

Incident and Fatality Analysis (Section 2.6):

- *Material and/or weld failures* is the primary cause of fatalities and led to the largest monetary loss in transmission failures; ~$6.3 billion (compared with $85 million for distribution lines), due to San Bruno, CA incident

Cause of Incidents (Section 2.7):

- *Corrosion* is the primary cause of failure in transmission incidents with 31% of the failures, followed by *material failure of pipe or weld* and *equipment failure*, at 17% each; eight incident causes were captured.

5. Recommendations

The study focused on a subset of the incidents in the PHMSA database, denoted ‘significant incidents’ per the criteria noted in terms of significant injuries/fatalities and monetary damage. The analysis could be further focused on the causes of high-risk events caused by ruptures leading to explosions.

The liquid pipeline incidents in the PHMSA database could be analyzed, to determine if similar trends and conclusions are reached.

The distribution data outlined in this report was limited to distribution main pipelines. If data are available, further analysis can be performed on the ~one million miles of service lines not accounted for in this report.

A logical extension to this work would be to review the steps PHMSA, DOT and other regulatory bodies are taking to reduce natural gas pipeline incidents and determine if they are consistent and address the major findings of this analysis as to primary causes of leaks, etc. Findings of this study could also be compared with recent work on leak detection and localization to ensure primary incident causes are being addressed (Murvay and Silea, 2012; Datta and Sarker, 2016).

This report also makes note of the criteria required for a pipeline incident to be reported. It is recommended that less severe incidents be tracked and analyzed by individual pipeline operators to guide further leak reduction measures.

It is important that steps continue to be taken to help prevent excavation damage, as well as other forms of unintentional damage to pipelines, such as being struck by a car or other motorized vehicle. This can be done through enhanced compliance with educational initiatives such as the 811-DIG hotline, Office of Pipeline Safety's *Shared Responsibility* campaign and the Common Ground Alliance. It is recommended that pipeline companies, as well as local governments, continue to work together to promote the development and reach of these programs.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jlp.2019.04.014.

Appendix A

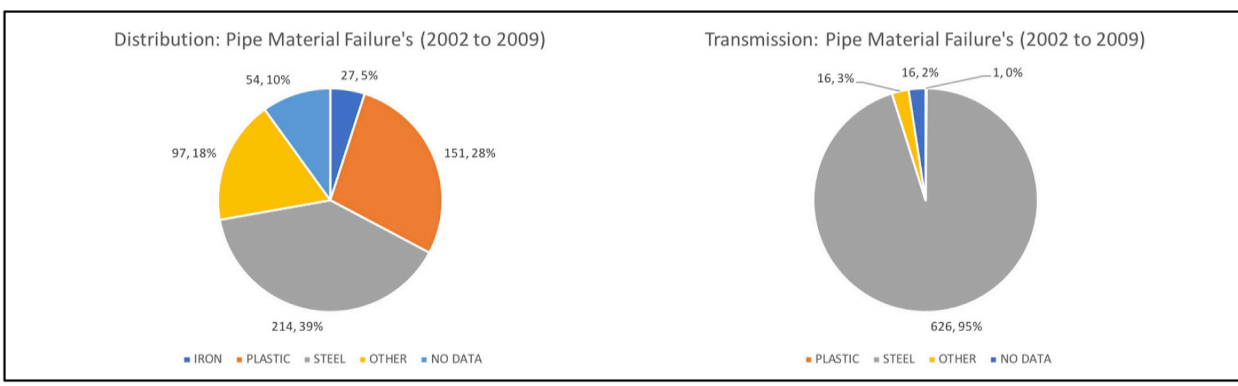


Fig. A.1. Distribution and transmission pipe material (2002–2009) (PHMSA, Pipeline Incident 20 Year Trends, 2018).

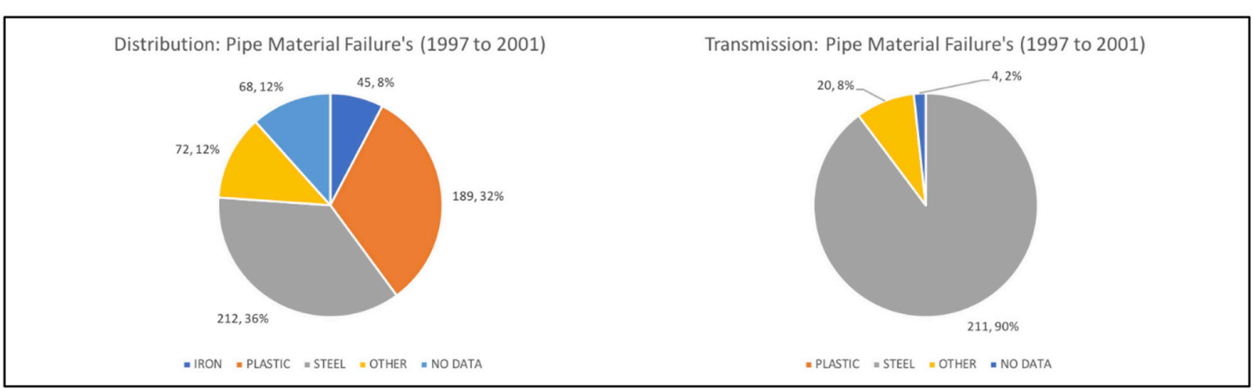


Fig. A.2. Distribution and transmission pipe material (1997–2001) (PHMSA, Pipeline Incident 20 Year Trends, 2018).

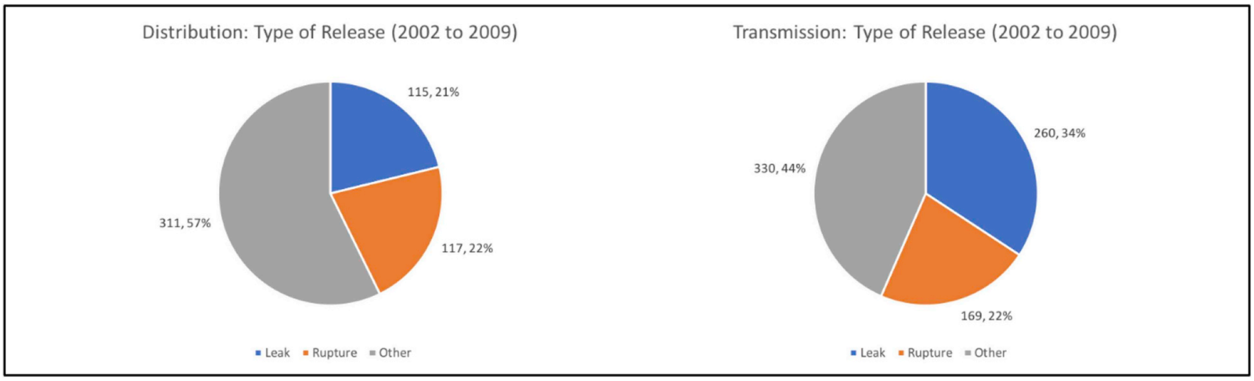


Fig. A.3. Distribution and transmission type of release (2002–2009) (PHMSA, Pipeline Incident 20 Year Trends, 2018).

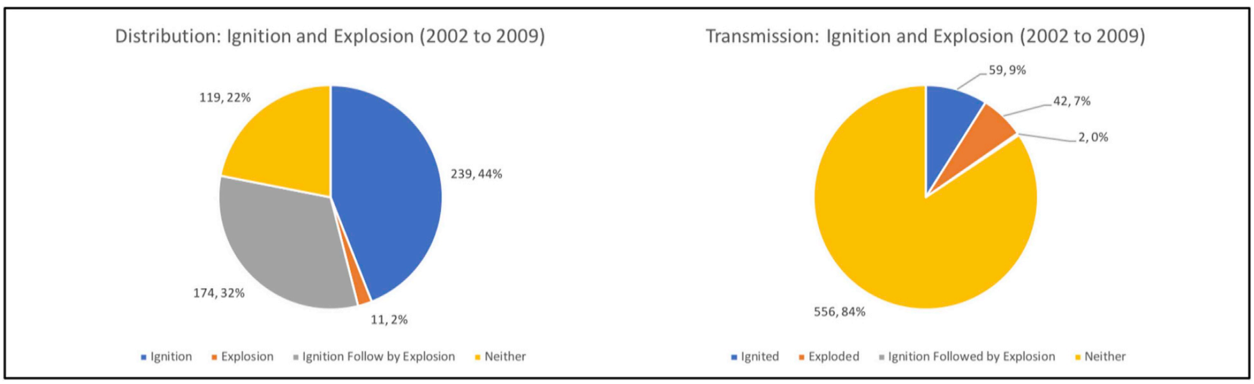


Fig. A.4. Distribution and transmission ignition and explosion results (2002–2009) (PHMSA, Pipeline Incident 20 Year Trends, 2018).

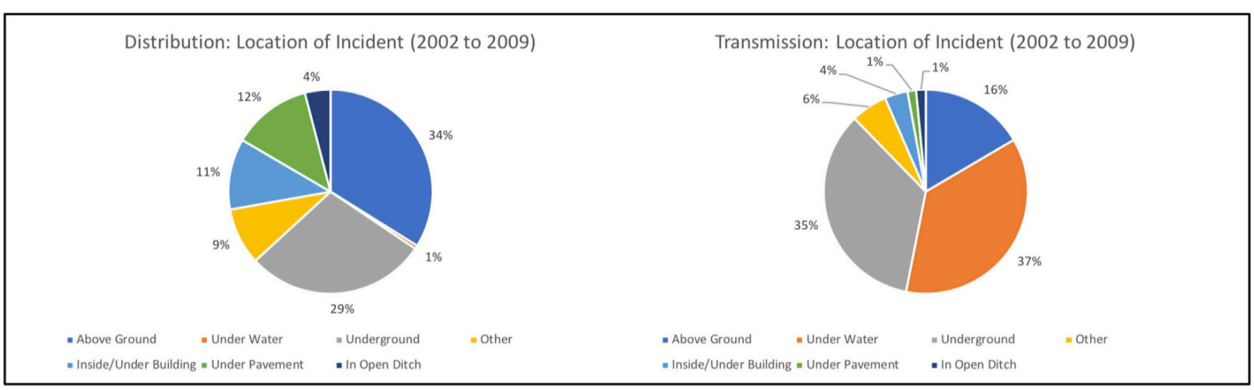
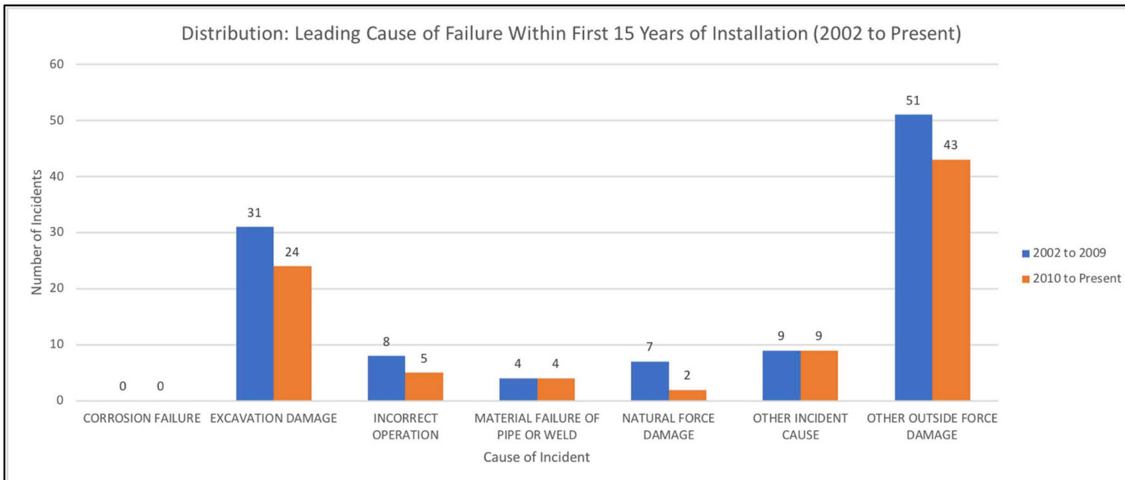


Fig. A.5. Distribution and transmission location of incident (2002–2009) (PHMSA, Pipeline Incident 20 Year Trends, 2018).



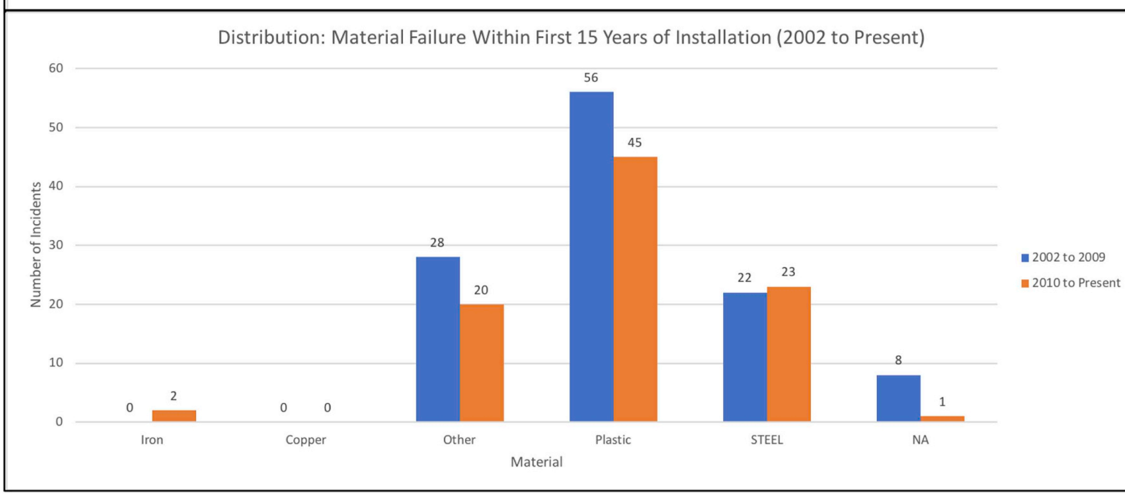


Fig. A.6. [TOP] Bar graph depicting the leading causes of failure when a pipe fails within the first 15 years of it being installed. [Bottom] Bar graph depicting the number of failures involved with specific material within the first 15 years of pipe installation (PHMSA, Pipeline Incident 20 Year Trends, 2018).

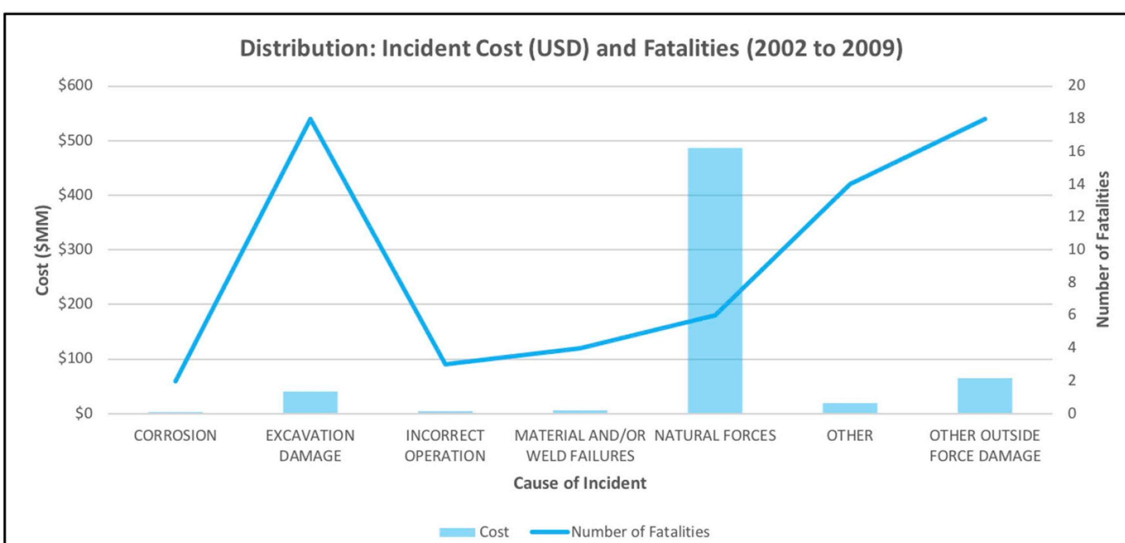


Fig. A.7. Distribution incident cost (USD) and fatality count (2002–2009) (PHMSA, Pipeline Incident 20 Year Trends, 2018).

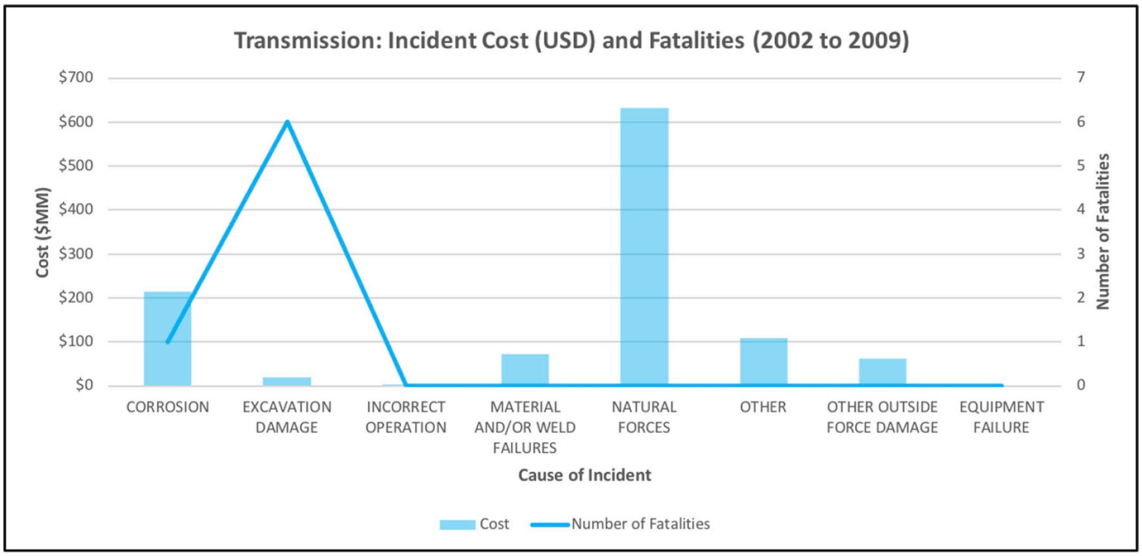


Fig. A.8. Transmission incident cost (USD) and fatality count (2002–2009) (PHMSA, Pipeline Incident 20 Year Trends, 2018).

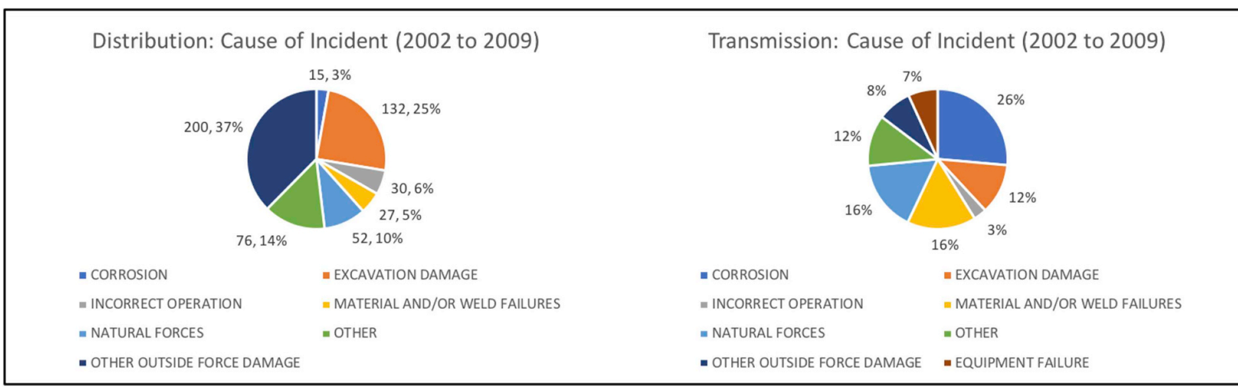


Fig. A.9. Causes of incident (2002–2009) (PHMSA, Pipeline Incident 20 Year Trends, 2018).

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