KAPITEL 1 / *CHAPTER 1* [1]
ACCIDENT PATTERNS IN OIL AND GAS PIPELINE DISTRIBUTION SYSTEMS

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Introduction

Transportation systems are vital to modern society, enabling the global movement of people, goods, and essential resources. As these systems become more complex and their capacity increases, the risk and potential consequences of accidents also rise. Despite ongoing efforts toward energy transition, global dependence on oil and gas remains significant. This persistent reliance underscores the importance of thoroughly investigating accidents in oil and gas transportation networks to inform policy, enhance safety standards, and mitigate future risks.

The history of commercial oil pipeline systems dates back to the 19th century, with early developments in Texas, USA, where crude oil was transported from production sites to refineries and ports. Notably, the Second Transcontinental Pipeline System—comprising the "Big Inch" and "Little Big Inch" pipelines was constructed during World War II for military purposes, linking Texas to the U.S. East Coast. These pipelines were acquired by the Texas Eastern Transmission Corporation in 1947, becoming a key component of America’s energy infrastructure.

Throughout the 20th century, the expansion of oil and gas pipelines kept pace with growing energy demands. In Europe, the Marshall Plan and the formation of the European Coal and Steel Community (ECSC) spurred the development of energy infrastructure. Technological advancements such as improved welding techniques and the use of high-strength materials (e.g., steel, polyethylene, composites) enabled the construction of longer and more resilient pipelines. Major European pipeline development gained momentum following the discovery of substantial oil fields in Romania and the Soviet Union. Initially centered on domestic resources in France,

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Italy, Germany, and Romania, the gas infrastructure expanded significantly in the 1970s and 1980s in response to the energy crisis. In the United States, the pipeline network is even more extensive, with over 480,000 km dedicated to natural gas gathering and transport, and an additional 3.5 million km for distribution. Pipelines dominate the transportation of natural gas and carry more than 90% of crude oil and petroleum products at some stage of their journey. Globally significant pipeline systems include the Trans-Alaska, Keystone, and Baku–Tbilisi–Ceyhan (BTC) oil pipelines, alongside the Nord Stream and Yamal–Europe gas pipelines. These networks are critical for cross-regional energy transport. However, the expansion of such infrastructure has heightened focus on safety. High-profile oil spills have prompted stricter regulatory frameworks and operational protocols. In the United States, early safety initiatives included the issuance of API RP 1104 (1960s) for welding standards and API RP 1110 for pressure testing in the 1970s. The American Society of Mechanical Engineers (ASME) introduced B31.4 and B31.8 standards for liquid and gas pipelines, respectively. The Office of Pipeline Safety, created in 1968, currently functions under the Pipeline and Hazardous Materials Safety Administration (PHMSA). The Natural Gas Pipeline Safety Act (1968), followed by the Pipeline Safety Act (1979), along with environmental legislation like the Clean Air Act (1970) and Clean Water Act (1972), further strengthened regulatory oversight. Technical standards from the American Petroleum Institute (API) and the Association of Oil Pipelines (AOPL) complement these regulations. While not legally binding, they are often incorporated into PHMSA's regulatory framework. For instance, API RP 1160 (2001–2019) outlines pipeline integrity management practices, API 1104 (1964–2021) governs welding, and API RP 1130 (2007–2022) focuses on computerized leak detection. In the European Union, pipeline safety is governed by a suite of legislative measures, including Directive 2013/30/EU on offshore oil and gas operations and Regulation 2017/1938/EU on gas supply security.

1.1 Literature research

Ensuring the integrity of pipelines is essential to maintaining safety and operational reliability in the oil and gas sector. This integrity is preserved through a combination of technical and procedural strategies focused on accident prevention, detection, and mitigation. The primary objective of these measures is to minimize the likelihood of incidents and reduce their potential environmental and economic impacts. Effective implementation involves rigorous planning, careful material selection, systematic maintenance, continuous monitoring, and robust emergency preparedness. Preventive strategies are designed to avoid damage before it occurs. These include sound engineering design, appropriate material selection, installation of safety valves, regular infrastructure maintenance, and on-site inspections. Although reliable, ground-based inspections can be hindered by difficult terrain and time constraints. As a result, aerial surveillance using aircraft or drones and legally mandated ground patrols are widely employed.

Modern technology plays a growing role in integrity management. Synthetic aperture radar (SAR) allows for consistent ground deformation monitoring, unaffected by weather conditions, making it valuable for detecting issues related to seismic activity, landslides, and erosion. Geographic Information Systems (GIS) integrate data from multiple sources to support enhanced risk assessment and pipeline route management. Pipeline maintenance includes the mechanical cleaning and internal inspection of pipelines using devices known as “pigs” (Pipeline Inspection Gauges). To prevent corrosion, buried or submerged pipelines are legally required to have protective external coatings. Over the past three decades, coating technology has significantly advanced, moving from traditional materials such as coal tar enamel and polyethylene to more durable options like fusion-bonded epoxy resins and three-layer polyolefin coatings. Cathodic protection, which applies direct current to the pipeline using rectifiers, is another key anti-corrosion measure. Additional safety features include mechanical dampers, flexible couplings to reduce vibration, and specialized rubber compounds for high-stress environments. Damage and leak detection rely on both conventional and advanced techniques. SCADA (Supervisory Control and Data Acquisition) systems offer continuous, real-time monitoring of pipeline parameters such as pressure, flow rate, and temperature. Caliper tools help identify deformations and pinpoint damage locations using GPS. Electromagnetic tools, like Magnetic Flux Leakage (MFL) detectors, identify cracks and corrosion by analyzing disruptions in magnetic fields, while machine learning enhances the accuracy of these assessments. Additional sensor-based technologies such as Hall effect, fluxgate, and magneto-sensitive sensors, as well as SQUIDs (Superconducting Quantum Interference Devices) support deeper diagnostics. Ultrasonic technologies also provide high-precision measurements of pipe wall thickness and internal flaws.

Inspection systems are increasingly optimized for resolution, accuracy, and localization, with improvements supported by GPS, automated control, and orientation tools. Advances in computing and imaging continue to improve fault detection capabilities. Emerging technologies include integrated ultrasonic and high-resolution three-axis MFL tools, robotic systems for inspecting low-pressure pipelines, UAV-assisted geolocation, and intelligent expert systems with machine learning capabilities for improved decision-making. Next-generation leak detection systems, such as Atmos Pipe and Atmos Eclipse, combine data from multiple sensors and use advanced algorithms to identify leaks early. Fiber optic systems offer continuous monitoring of temperature and acoustic signals along pipeline routes, providing high precision even in remote or challenging terrain. Notably, Atmos Eclipse supports rapid, non-invasive installation and autonomous operation in inaccessible areas. Mitigation strategies are crucial for effective incident response. These include access to safety data sheets detailing the properties and hazards of the transported materials, and ensuring personnel are properly trained for emergency procedures. Legal mandates require engagement with authorized emergency services. Industry guidelines, such as the *Pipeline Emergency Response Guidelines* developed by the Pipeline Association for Public Awareness (PAPA), provide essential instructions for effectively handling incidents involving aboveground or underground pipelines. Despite significant progress, the safety of oil and gas pipelines remains a critical concern. Numerous studies have examined accident trends, failure mechanisms, and risk mitigation strategies, reflecting continued efforts by researchers and institutions to enhance pipeline integrity. As technological advancements and increased industry awareness have altered the frequency and nature of incidents, recent literature has focused on contemporary developments to ensure relevance.

Khan et al. [1] traced the evolution of pipeline safety management from visual inspections to advanced, risk-based systems leveraging real-time data, exploring key issues in integrity management and the influence of Industry 4.0. Chen et al. [2] conducted a bibliometric analysis of 598 publications (1970–2019), identifying risk assessment, leakage, and corrosion as dominant themes, with fuzzy theory and Bayesian networks as prevalent methodologies. Kraidi et al. [3] examined risk management practices in unstable regions, highlighting the challenges posed by limited data and low safety standards. Using document analysis and industry surveys, they identified terrorism, corruption, and unsafe conditions as primary risks, analyzed through fuzzy logic.

Several studies focus on specific causes of pipeline failures. For instance, Yu et al. [4] used nonlinear finite element analysis to study the behavior of suspended pipelines under natural disasters, examining variables such as span length and pressure to develop emergency strategies. Korlapati et al. [5] reviewed leak detection methods, evaluating their performance, advantages, and limitations. Other researchers addressed how digitalization, smart technologies, and the low-carbon transition influence pipeline safety, noting that while these innovations lower operational costs, they also introduce new risks. Woldesellasse and Tesfamariam [7] conducted a comprehensive literature review of four decades of pipeline safety research, with a focus on risk assessment and failure prediction using methods like fuzzy logic and simulations. Their study highlights a research gap concerning post-failure impacts, such as environmental and financial consequences, and calls for broader application of technologies like GIS and machine learning. They also identified China, Canada, and the U.S. as leading contributors to pipeline safety research. Given the high stakes of oil and gas accidents, understanding their causes, frequency, and patterns is vital. Incident databases are key tools for this, capturing operational conditions, failure modes, and consequences. However, disparities in classification criteria, geographical scope, and data granularity hinder cross-regional comparisons and comprehensive understanding. Standardized data collection practices are therefore essential. Halim et al. [8] addressed this by comparing data from PHMSA, Canada's NEB, and EGIG, revealing how different reporting systems affect the classification and analysis of incidents.

Alves and Lima [9] proposed the development of a national pipeline incident database for Brazil. Based on international standards and expert input, they outlined a framework for data collection and demonstrated its application through root cause analysis. Although many studies rely on individual databases (e.g., PHMSA, EGIG) for statistical assessments, few systematically compare multiple sources in terms of methodology, definitions, or coverage. Failure rates and causes differ significantly across regions due to factors such as infrastructure age, geological conditions, maintenance practices, technical standards, political stability, and regulatory oversight. This review focuses on the most significant national and international databases including EGIG, CONCAWE, eNatech, the Transportation Safety Board of Canada (TSB), PHMSA, and the U.S. National Response Center. These platforms offer insights not only into the causes of pipeline failures but also into broader trends and cause-effect relationships. The core aim of this work is to evaluate the structure and content of these databases and conduct an integrated qualitative analysis of accident causes. By synthesizing data from multiple sources, this study provides a comprehensive overview of how accidents occur, their interdependencies, and their operational context. A comparative analysis of statistical data across regions also highlights differences in practice, awareness, and system reliability essential information for shaping future energy infrastructure and policy planning.

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1.2 Analysis of the publicly available data from TSO and public databases.

The systematic collection of pipeline accident data has been undertaken by numerous organizations worldwide, serving as a foundational element for developing effective prevention strategies and enhancing safety standards. Historical accident data is particularly valuable in risk management decision-making, which is vital for maintaining industrial safety. In the European Union, the *eNatech* database managed via the “Europa.eu” portal serves as a central repository for technical accidents triggered by natural disasters, known as *natech* events [10,11]. Research into natech accidents began in the late 1970s, initially focusing on seismic events before expanding to include hydrometeorological hazards such as floods, storms, and multi-hazard interactions. This broader scope has allowed researchers to better understand the complex nature of natech-related risks. As of 2023, the eNatech database contains 13 recorded pipeline accidents (1979–2023), with landslides accounting for 61.5% of the incidents, followed by earthquakes (23.1%), lightning (7.7%), and flooding (7.7%). Another key resource is the European Gas Pipeline Incident Data Group (*EGIG*), established in 1982. EGIG annually collects incident data from 19 network operators. Its scope is limited to onshore steel pipelines operating above 15 bar and excludes pipelines within gas facilities. Incidents must involve unintentional gas releases. While the raw data is not publicly available, EGIG regularly publishes analytical reports, which include historical trends (since 1970), failure frequencies, and classifications of accident causes into six categories: external interference, corrosion, construction or material defects, erroneous hot tapping, ground movement, and other/unknown causes. Landslide-related incidents, as well as those caused by dam failures or mining activities, fall under the ground movement category. Lightning-related events are grouped within "other/unknown" [12].

Accident frequency is assessed using two metrics: *primary* frequency (based on total exposure, measured in pipeline length and operational time) and *secondary* frequency (based on partial exposure by design parameters). Total system exposure amounts to 5.29 million km·year. Over time, the primary failure frequency has declined from 0.875 per 1,000 km·year in 1970 to 0.277 per 1,000 km·year in 2022. Secondary frequency assessments provide insight into the influence of specific design features such as diameter, coating, wall thickness, and construction year on failure probability. Data analysis indicates that failure frequency generally decreases with increasing pipeline diameter. Smaller-diameter pipelines are more vulnerable to external

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interference, likely due to thinner walls, more urban installations, and higher susceptibility to earthworks. Wall thickness is a critical factor no incidents were recorded in pipelines with walls thicker than 20 mm, and corrosion-related failures were absent in pipelines with walls over 15 mm. Pitting corrosion, primarily affecting external surfaces, is the most common form, followed by cracking, which can occur on both inner and outer surfaces. Modern pipelines are more resilient due to improved materials and coatings. Polyethylene-coated pipelines show significantly lower failure rates than those with earlier coating types. Most contemporary gas transmission operators have adopted polyethylene coatings as the industry standard.

In addition to causes and frequencies, EGIG data includes information on casualties. Injuries and fatalities are categorized into four groups: gas company employees, third-party personnel, emergency responders, and the general public. Out of 1,463 recorded incidents, only about 1% involved injuries and 0.7% resulted in fatalities [12]. The CONCAWE database includes onshore pipelines used for transporting crude oil or refined petroleum products that are at least two kilometers long. It excludes subsea pipelines, terminals, and storage tanks, but includes pumping stations and buffer storage facilities. The database mainly records spills exceeding 1 m^3 of hydrocarbons, though smaller incidents are also documented if they pose notable safety or environmental risks. As of the latest report [13], the European oil pipeline network comprises 35,307 km of pipelines operated by 68 companies and agencies. These pipelines are categorized as:

- **Crude pipelines** – for transporting crude oil.
- **Hot pipelines** – for transporting viscous products like heavy fuels, lubricants, and waxes, which require elevated temperatures.
- **Products pipelines** – for distributing various refined petroleum products.

Pipeline dimensions vary by type. Nearly 90% of crude oil pipelines have a nominal diameter of ≥400 mm (16 in). Conversely, 85% of product pipelines and over 80% of hot pipelines have diameters below 400 mm and 600 mm, respectively. Since 1971, 278 pipeline sections totaling 11,848 km have been decommissioned. The average age of active pipelines is approximately 40 years, presenting growing

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challenges in maintenance and safety. Over more than 50 years of reporting, the CONCAWE database has recorded five fatal accidents (in 1975, 1979, 1989, 1996, and 1999), resulting in 14 fatalities, mostly due to fires following hazardous substance releases. In total, 789 spill incidents have been recorded. Spill causes are categorized into five main groups:

1. **Mechanical failures** – including design and material defects.
2. **Operational causes** – encompassing system and human errors.
3. **Corrosion** – subdivided into internal, external, and stress corrosion cracking.
4. **Natural disasters** – primarily ground movement and other geohazards.
5. **Third-party activities** – such as accidental, incidental, or intentional interference.

Over time, the release frequency has declined significantly. The five-year moving average fell from 1.1 releases/year/1,000 km in the mid-1970s to 0.09 releases/year/1,000 km by 2022. Although annual spill volumes vary, the long-term trend is downward. Spill impact data show that 40% of incidents affected areas between 100–999 m^2, with average volumes sharply increasing for larger spills (10,000–99,999 m^2), reaching approximately 800 m^3 per incident.

Breakdown by Pipeline Type and Cause

- **Hot pipelines**: Corrosion is the dominant cause (81%) of leaks.
- **Oil pipelines (cold pipelines)**: The leading causes are third-party activities (37%) and mechanical failure (31%), followed by corrosion (21%).

From 1971 to 2022, mechanical failures resulted in 142 incidents (18% of all leaks), including 54 due to design flaws and 88 due to material defects. Only 10 incidents were attributed to aging and fatigue. When theft-related events are included, mechanical failure accounts for 19% of cold pipeline incidents. Operational causes were responsible for 38 spill incidents over the same period representing 8% of cold pipeline incidents (5% if thefts are included). Corrosion led to 147 accidents (2.8 leaks per year), with external corrosion being the most prevalent, especially in hot pipelines. Oil pipelines are more prone to internal corrosion, owing to the chemical properties of crude oil. Natural disasters accounted for 2–3% of oil pipeline accidents, with most

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attributed to ground movement. At least 10 incidents occurred in a single country with challenging terrain and water conditions. Third-party interference was involved in 445 events, or 56% of cold pipeline releases:

- **Accidental damage**, often from excavation due to poor communication.
- **Intentional damage**, such as vandalism or attempted theft.
- **Latent failures**, which may only manifest long after the initial disturbance.

Depending on whether theft is considered, third-party actions account for 37% to 61% of all cold pipeline incidents. In the most recent period (2018–2022), mechanical failures remained the leading cause of pipeline accidents, except in 2019, when corrosion and operational issues were more prominent. The ARIA (Analysis, Research, and Information on Accidents) database, managed by France's Bureau for the Analysis of Industrial Risks and Pollution (BARPI), has been documenting selected industrial, agricultural, and hazardous goods transport accidents—both domestic and international—since 1992. With over 46,000 entries and 1,200 new cases added annually, ARIA serves as a repository for incidents that provide experience-based insights into risk prevention. The database includes pipeline accidents and employs evolving selection criteria to align with technological advancements. Each record typically includes a short description primarily in French, though some are available in English and can be searched using an online interface. Accidents are classified using the European Industrial Accident Scale, which evaluates incidents across four categories: hazardous material releases, human and social impact, environmental damage, and economic loss. In the U.S., the Pipeline and Hazardous Materials Safety Administration (PHMSA) oversees pipeline safety regulations. PHMSA has monitored pipeline incidents since 1970, covering gas distribution, transmission, gathering systems, and hazardous liquids. Reportable incidents, originally defined by thresholds such as death, injury, fire, or economic loss, have undergone several updates—most recently in 2021, which raised the reporting threshold for property damage to USD 122,000. PHMSA also expanded its definitions to include LNG and underground gas storage facilities. Publicly available reports provide detailed information on the nature, location, causes, and costs of incidents, excluding events triggered by safety systems without actual hazard.

In Canada, the Transportation Safety Board (TSB), established in 1990, investigates pipeline, rail, marine, and aviation accidents. Operating independently, it identifies safety deficiencies and issues recommendations that influence national and international safety practices. In 2023, 68 pipeline accidents were recorded—33% below the 10-year average, with no fatalities reported since the TSB’s inception. Canada’s 68,200-kilometre pipeline network transported significant energy volumes that year. TSB categorises incidents and accidents according to national regulations and publishes both monthly and annual statistical summaries. A comparison of the EGIG, CONCAWE, PHMSA, and TSB datasets reveals notable regional differences in the causes of pipeline incidents. In Europe, third-party activities and corrosion are the most frequent causes of gas and oil pipeline accidents (27–37% and 21–26%, respectively). In the U.S., corrosion and excavation damage each account for about 32% of accidents, indicating the need for robust corrosion management and monitoring of construction activities near pipelines. In contrast, Canadian data show a predominance of geotechnical, hydrological, and environmental causes (35%), with third-party impacts playing a smaller role (approximately 20.6%). Despite offering valuable insights into the common causes and risks associated with pipeline transport, these datasets have limitations. They vary in scope e.g., EGIG focuses on gas pipelines, CONCAWE on oil, and PHMSA distinguishes between various pipeline types and span different timeframes and geographical regions. Furthermore, the analysis does not account for factors such as pipeline length, transport volume, or age, limiting comparability. As such, findings reflect absolute incident counts and percentages, not normalised risk levels.

Conclusion

Ensuring safety in increasingly complex oil and gas transport systems depends on standardised technical rules and regulatory frameworks. These rely on a systematic safety approach integrating prevention, detection, and mitigation measures. Modern technologies such as real-time monitoring systems, advanced sensors, and data analytics enhance the early detection of potential failures, enabling timely interventions and more effective accident mitigation.

To reduce corrosion-related incidents, regulatory standards could require inline inspection tools for pipelines exceeding specific age and diameter thresholds, especially for those transporting crude oil. Such measures would strengthen safety by combining regulatory enforcement with technical monitoring practices. Increased inspection frequency would also help mitigate incidents stemming from human error, equipment malfunction, and environmental factors. Historical accident data is essential for understanding risk patterns and informing future safety improvements. Long-term data collection efforts by organisations such as EGIG, CONCAWE, PHMSA, TSB, and eNatech have contributed to global knowledge on pipeline incidents. Comparative analyses of these databases enable the identification of best practices and risk factors relevant to future energy infrastructure planning. Key conclusions include:

- **Database applicability varies by context**: EGIG is optimal for gas pipeline studies in Europe, while CONCAWE is well-suited for analysing oil pipeline safety and environmental risks. PHMSA provides the most comprehensive data for the U.S., and TSB offers detailed statistics with broad influence on North American safety standards.
- **Limited utility of ARIA and eNatech**: ARIA's empirical focus limits its representativeness for broader statistical analysis, and eNatech is specialised for natural hazard-related ("Natech") accidents.
- **Regional differences** exist in pipeline accident causes, with notable variation between Europe, the U.S., and Canada.
- **Accident causation patterns**: The majority of recorded incidents fall under "Human and Operational Failures" (40.2%) and "Corrosion and Material Damage" (30.15%), while "Extraordinary Events and Safety Failures" account for just 4.1% but may carry high severity.

Overall, enhanced monitoring, appropriate regulatory measures, and robust use of historical data are key pillars in advancing pipeline safety and resilience.

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