International Journal of Hydrogen Energy 57 (2024) 107–120

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he

Comparing the risk of third-party excavation damage between natural gas and hydrogen pipelines

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ARTICLE INFO

Keywords:
Hydrogen safety
Pipelines
Pipeline integrity
Bayesian network
Quantitative risk assessment

ABSTRACT

Existing natural gas pipelines can facilitate low-cost, large-scale hydrogen transportation and storage, but hydrogen may entail safety challenges. These challenges stem from hydrogen's different properties compared to natural gas, such as higher ignition probability, different flame behavior, and potential for hydrogen embrittlement. Although risk assessments for hydrogen pipelines are increasing, the impact of hydrogen on the risk of third-party excavation damage (TPD), the major cause of pipeline incidents in the U.S., has received little attention. This work presents the SHyTERP model for Safe Hydrogen Transportation and Excavation Risk Prevention for Pipelines. The model incorporates causal models, excavation damage and pipeline failure statistics, and validated physical models of hydrogen and natural gas release and jet flame behavior. Through four case studies, the model compares the TPD risks of hydrogen and natural gas pipelines, offering insights and recommendations for the safe implementation of hydrogen in existing pipelines.

1. Introduction

To enable the wider adoption of hydrogen technologies and make efficient use of existing infrastructure, the natural gas pipeline network is being considered as a way to transport hydrogen to facilities such as industrial sites and distribution centers. Several programs are being implemented in the U.S. to blend up to 20% of hydrogen into natural gas pipelines, which is expected to be a short-term, safe, and cost-effective path towards hydrogen transportation [1–3]. Although blending will be needed in the early stages of hydrogen delivery to facilitate economies of scale and generate demand, the ultimate goal is to transport pure hydrogen in existing pipelines to achieve U.S. net-zero objectives by 2050 [4]. However, transporting pure hydrogen through existing natural gas pipelines poses safety challenges concerning hydrogen embrittlement of steels, higher pressures, a wider range of flammability limits, and different fire behavior, among others [5]. Safety-relevant properties are shown for natural gas and hydrogen in Table 1. Whether these differences will actually cause meaningful differences in pipeline safety is an open question. Quantitative risk assessment (QRA) provides a tool for assessing the safety implications of hydrogen transportation through existing pipelines and obtaining insight into the causal factors responsible for any differences.

Several researchers have conducted QRA for hydrogen transportation through existing natural gas pipelines, but they largely assume that failure frequencies are similar to those for natural gas. For example, Froeling et al. [6] performed a QRA on high-pressure transmission pipelines and studied the individual risk associated with a hydrogen jet fire from a rupture. Although they account for the higher ignition probability of hydrogen, the frequency of pipeline rupture events was assumed to be the same for both hydrogen and natural gas. Likewise, Witkowski et al. [7] performed a QRA on both jet fire and explosion hazards in a ruptured transmission pipeline and provided individual risk profiles for hydrogen, natural gas, and blend releases. They accounted for hydrogen embrittlement in their assessment by modeling it as a new independent failure cause. However, to do so, they just assumed that embrittlement would have a frequency equivalent to corrosion damage. No further justification was made regarding the validity of this decision. Several other works have studied different risks posed by hydrogen transportation through pipelines [8–12]. However,

Table 1
Safety-relevant properties for hydrogen and methane.

Properties	Hydrogen	Methane
Flammability limits	4%–75%	5%–15%
Maximum laminar burning velocity, m/s	2.7	0.4
Minimum ignition energy, mJ	0.017	0.29
Detonation cell width, cm	1	30
Density relative to air	0.07	0.55
Speed of sound (sonic releases), m/s	1290	460
Combustion energy at LFL, MJ/m^3	0.5	2.0

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https://doi.org/10.1016/j.ijhydene.2023.12.195
Received 28 July 2023; Received in revised form 14 December 2023; Accepted 19 December 2023
Available online 8 January 2024

these mainly focus on the consequences of events rather than modeling any causal drivers behind these events. Furthermore, treatment of third-party excavation damage (TPD), the leading cause of pipeline incidents in the U.S. [13], is a concerning causal driver that has been neglected in current QRAs for hydrogen pipelines.

TPD is accidental damage to a pipe in an excavation activity performed by a party not associated with the utility company managing the pipe. TPD is one of the major threats to pipeline integrity nowadays and could be a challenge to the future of hydrogen transportation through existing pipelines. According to the Pipeline Hazardous Material and Safety Administration (PHMSA) [13], TPD is the cause of more than 20% of U.S. pipeline incidents, and from 2016–2022 it resulted in 11 fatalities, 36 injuries, and over $144M in damages. Moreover, although there is a well-defined set of best excavation practices [14], excavation damage trends have remained constant over the years [15]. As such, TPD must be appropriately addressed in pipeline QRA. While risk models have addressed causes of TPD to pipelines (see [15] for a detailed discussion), these models have not been connected to the consequences of that damage. Furthermore, no risk research has studied how the risk of TPD differs between natural gas and hydrogen uses, even though there is evidence suggesting that both the probability and consequences of TPD can be different in a hydrogen setting compared to natural gas [16–18].

In steel pipelines, hydrogen affects several important properties that could increase the likelihood and severity of TPD incidents. Hydrogen embrittlement can lead to degradation and decreased fracture toughness, ductility, and impact resistance, of the carbon steels commonly used in transmission and distribution pipelines [17,19–22]. The material property changes caused by hydrogen can increase the vulnerability of pipelines to dents, gouges, and punctures caused by TPD. For instance, Zhang and Adey [18] found that hydrogen can significantly increase the probability of delayed failures from excavation-caused dents in high-pressure transmission pipelines. It stands to reason that embrittlement could similarly increase the likelihood of puncture, which causes the most severe consequences in pipeline incidents, according to PHMSA research [23].

While the material integrity of plastic pipelines used for natural gas distribution has been found to be unaffected by pure hydrogen transportation [24], plastic pipes are more susceptible to being punctured in excavations than metallic pipes [25]. Moreover, the resulting gas released from plastic pipelines could be more likely to ignite immediately due to static electricity buildup in plastics [26]. In general, the ignition probability for hydrogen releases is consistently higher than that of natural gas for different gas-air mixtures [27], owing to hydrogen's low ignition energy (0.017 mJ vs. natural gas' 0.3 mJ) and wide flammability range (4%–75% vs. natural gas' 5%–15% in volume in air) [28]. Therefore, TPD risks for plastic pipelines may not be immune from the effects of hydrogen.

As can be seen, punctures, immediate ignitions, and, therefore, jet fires could be significantly more probable in a hydrogen setting. Additionally, jet fire severity could also increase due to potentially higher operational pressures needed to account for hydrogen's lower energy density and meet current energy demands (12.7 MJ/m^3 vs. natural gas' 40 MJ/m^3) [16,29]. These higher operational pressures can lead to larger jet fires and higher heat radiation and temperatures when compared to similar natural gas fires [30].

Despite these challenges, there are other aspects of hydrogen that suggest its transportation through existing pipelines could be safer than natural gas. For instance, hydrogen disperses faster in the air than natural gas due to high buoyancy and diffusivity, which reduces the likelihood of the formation of combustible clouds and explosions in unconfined or well-vented areas [28]. Additionally, at similar pressure, hydrogen fires are expected to be smaller in size and to have lower heat radiation, overall, compared to natural gas fires, thus reducing the risk of thermal harm at some locations [6]. However, as mentioned earlier, hydrogen pipelines are likely to operate at higher pressure to meet current energy demand.

It is clear that assessing the risk of TPD for hydrogen and natural gas in pipelines requires a more comprehensive set of variables and models that have been established in previous studies. It is necessary to understand the complex interplay between the aforementioned differences in gas properties, flame behaviors, system design, and operational conditions that affect risk. Furthermore, it is necessary to capture the interdependent causes of excavation damage, many of which also differ in hydrogen vs. natural gas pipelines and thus affect both the likelihood and consequences of such events.

To address this need, we developed a novel causal model to assess the risk of TPD to hydrogen and natural gas pipelines. This model employs a Bayesian network approach that leverages multiple data sources – including past incidents, nationwide statistics, and expert knowledge – to simulate and obtain insights about third-party excavations, punctures, ignited releases, and thermal harm caused by jet fires. Furthermore, the model is based on causal modeling principles, enabling the model to be used to understand the causal drivers responsible for any differences between hydrogen and natural gas pipeline TPD risk.

To evaluate the differences between hydrogen and natural gas pipeline risk, we used the model to conduct four case studies designed to provide insights and recommendations that would support the safe transportation of hydrogen through existing natural gas pipelines. Case study 1 provides a baseline comparison between TPD risks of puncture, ignition, and jet fires for both hydrogen and natural gas. Case study 2 evaluates how the risk of TPD changes for distribution systems comprising different shares of steel and plastic pipelines. Case study 3 evaluates how past incidents in transmission pipelines could have changed had hydrogen been transported instead of natural gas. Case study 4 identifies the factors that are most responsible for the differences in TPD risk that hydrogen and natural gas pipelines may pose.

The rest of this work is as follows: Section 2 provides the methods and data used to develop the model. Section 3 describes the methodology used to construct, parameterize, and use the model. Section 4 shows the resulting risk model for TPD and its outcomes. Section 5 presents the results of case studies and provides causal insights on the risk of TPD to hydrogen pipelines. Finally, Section 6 concludes with recommendations for the safer transportation of hydrogen through natural gas pipelines and provides directions for future work.

2. Data and methods

2.1. Information sources

This work leveraged an extensive set of data sources and models. We used two primary models, both of which contain a large amount of information and data about aspects of TPD scenarios and hydrogen and natural gas behaviors. The first was the *BaNTERA (A Bayesian Network for Third-Party Excavation Risk Assessment)* model, a causal model of TPD [15]. The second was the *HyRAM+ (Hydrogen Plus Other Alternative Fuels Risk Assessment Models)* software toolkit and algorithm developed by Sandia National Laboratories [31,32],

The BaNTERA model [15] provides a comprehensive quantitative model of causal factors relevant to TPD risk assessment and includes a taxonomy of the actors, objects, and environments relevant to a third-party excavation activity. Furthermore, BaNTERA provides a structure describing an excavation process, subsequent puncture damage, and conditional probabilities describing the dependencies between these variables and their causal relationship to damage. The model structure and probabilities were informed by a large body of data summarized below and described in detail in Ruiz-Tagle et al. [15].

BaNTERA incorporates two previous models from GTI Energy, one for the causes of locating and marking errors [33] and one for the causes of TPD and puncture probability [25]. These models were integrated and augmented with additional information in BaNTERA. BaNTERA also includes two databases from PHMSA. The PHMSA annual report on natural gas pipeline mileage and facilities from 2021 [34] were used to inform the characteristics of existing pipelines, such as materials and sizes in transmission and distribution systems. Additionally, PHMSA's incident reports from 2016–2021 [13] were used to support the development of BaNTERA's TPD root cause nodes.

BaNTERA also uses utility excavation notifications, including over 7000 TPD reports collected by a U.S. utility from 2016–2021. The raw data includes more than 40 fields describing an excavation context and damage causes, which were used to inform the context and causes of excavation damage in the BaNTERA model [15]. This data was augmented with additional records from the Common Ground Alliance (CGA), a non-profit organization that provides best practice guides [14] as well as incident statistics to inform damage prevention and safety of underground utilities through its DIRT database [35]. In CGA's DIRT, more than 35,000 voluntary damage reports are recorded every year; DIRT data from 2019–2022 were used to parameterize BaNTERA. In our current work, we further modified aspects of the BaNTERA model as described in Section 3.

The second major source of information was the HyRAM methodology and the HyRAM+ software toolkit and algorithm [31,32]. HyRAM integrates dozens of state-of-the-art models and data sources into a common platform for enabling QRA and consequence analysis for hydrogen systems. HyRAM includes validated models for simulating both hydrogen and natural gas releases in a puncture scenario, plume dispersion, and a subsequent jet flame's temperature, trajectory, and radiative heat flux. HyRAM+ is available as a Python API, enabling its integration with external models and its use on a probabilistic framework by allowing the simulation of a gas release under multiple scenarios.

In addition to the information sources described above, we reviewed and used a wealth of academic literature to support modeling decisions and assumptions, as it is further detailed in Section 3.1. Additionally, our work used two standards and one code to inform existing pipeline characteristics. The API 5L [36] and ASTM D2513 [37] specifications for steel and plastic pipes, respectively, were used to correlate a pipe size with its wall thickness. Finally, we used the U.S. code of federal regulations CFR49.192 [38] on natural gas pipeline safety to inform the dependencies between a pipe size, material, and wall thickness with its design pressure.

2.2. Causal Bayesian networks

Bayesian networks are widely used in risk assessment as a causal model to represent the joint probability distribution of the variables describing the states of a system or process [39]. As such, Bayesian networks are propitious to incorporate the information sources described in Section 2.1.

A Bayesian network model M represents variables $V = \{V_1, \dots, V_n\}$ and their dependencies as the nodes and edges of a directed acyclic graph G. The dependencies among variables are modeled as conditional probability distributions $Pr(V_i \mid V_j)$. A Bayesian network is called "hybrid" if both discrete and continuous variables are modeled. Mathematically, the joint probability distribution of the states of a system or process can be computed using a Bayesian network model using the following equation:

$$Pr(V_1, \dots, V_n) = \prod_{i=1}^{n} Pr(V_i \mid pa(V_i)) \quad (1)$$

where $pa(V_i)$ corresponds to the "parent nodes" of node V_i; that is, all nodes in $G \in M$ with an outgoing edge into V_i. Furthermore, a causal Bayesian network model assumes that $pa(V_i)$ causes V_i. All Bayesian networks constructed in this work will be hybrid and causal.

Bayesian network models enable causal inference under uncertainty [40]. Causal inference helped us to understand risk and find insights for TPD safety in future hydrogen pipelines. Bayesian networks can answer three types of causal queries: associations, interventions, and counterfactuals. Associations assess how new evidence $V_i = v_i$ on V_i changes the probability of $V_j = v_j$. Association queries are written as $Q = Pr(V_j = v_j \mid V_i = v_i)$ [40], and they are the most commonly used in risk assessments [41]. Interventions assess how setting/intervening $V_i = v_i$ on V_i changes the probability of $V_j = v_j$. Intervention queries are written as $Q = Pr(V_j = v_j \mid do(V_i = v_i))$, and Ruiz-Tagle et al. [41] show how to compute them for risk assessments. Counterfactuals assess how changing V_i from $V_i = v_i$ to $V_i = v_i'$ could have changed V_j from $V_j = v_j$ to v_j' in a past event. Counterfactuals are written as $Q = Pr(V_{j_{V_i=v_i'}} = v_j' \mid V_j = v_j, V_i = v_i)$, and Ruiz-Tagle et al. [42] show how to compute them for risk assessments. Bayesian network's causal inference capabilities were fundamental to inform the four case studies described in Section 1.

All Bayesian networks in this work were built using BayesFusion's GeNIe software [43], while simulation and inference were done using BayesFusion's `pysmile` Python library [44].

3. Methodology for assessing the risk of excavation damage to hydrogen pipelines

This work proposes a novel methodology (see Fig. 1) for developing a model that assesses the risk of TPD to natural gas and hydrogen pipelines. The methodology can be summarized as follows: The data sources in Section 2.1 were integrated to construct and parameterize four dependent Bayesian network models. These models capture the characteristics of the U.S. pipeline system, an excavation and its context, the conditions leading to puncture damage, and the scenarios that may cause ignited gas releases and potential harm. Then, we used these Bayesian networks to simulate excavations, punctures, ignited releases, and thermal harm from jet fires. These simulations utilize Monte Carlo methods and causal inference techniques to generate probabilistic outcomes. The goal of these simulations was to provide valuable insights that contribute to the ongoing discussion regarding the utilization of hydrogen in natural gas pipelines, as well as the risks associated with TPD. In the subsequent sections, we provide a detailed description of our risk modeling methodology and outline the scenario simulations conducted to evaluate the potential impact of TPD in a hydrogen setting.

It is important to highlight that this modeling effort only considers jet fire hazards and thermal harm, but deliberately omits explosion hazards and overpressure effects. Explosion modeling and consequences are highly dependant on the location in which a release occurs (such as determining obstructed areas, source strengths, among others). As such, case-specific studies should address the risks associated with explosions. This point is identified and suggested as future work in Section 6.

3.1. Model construction

The bow-tie diagram in Fig. 2 shows the main safety barriers to preventing a hazardous gas release during a third-party excavation activity. A safe excavation involves notifying the authorities, marking the pipelines at the site, and following best digging practices [14]. Otherwise, pipeline damage and gas release can happen. A jet fire event can result from gas ignition and harm nearby people without any chance of fast recovery actions, such as stopping the gas flow or implementing emergency response plans. However, the bow-tie of Fig. 2 does not capture the complexity of a TPD event. A hazardous release involves many variables that interact in an excavation process, its context, and potential puncture and gas release (dashed nodes and arcs in Fig. 2). As such, the following four dependent sub-models were created to account for the complexities and interactions involving TPD, pipeline characteristics, and hydrogen and natural gas behaviors, as shown in Fig. 1:

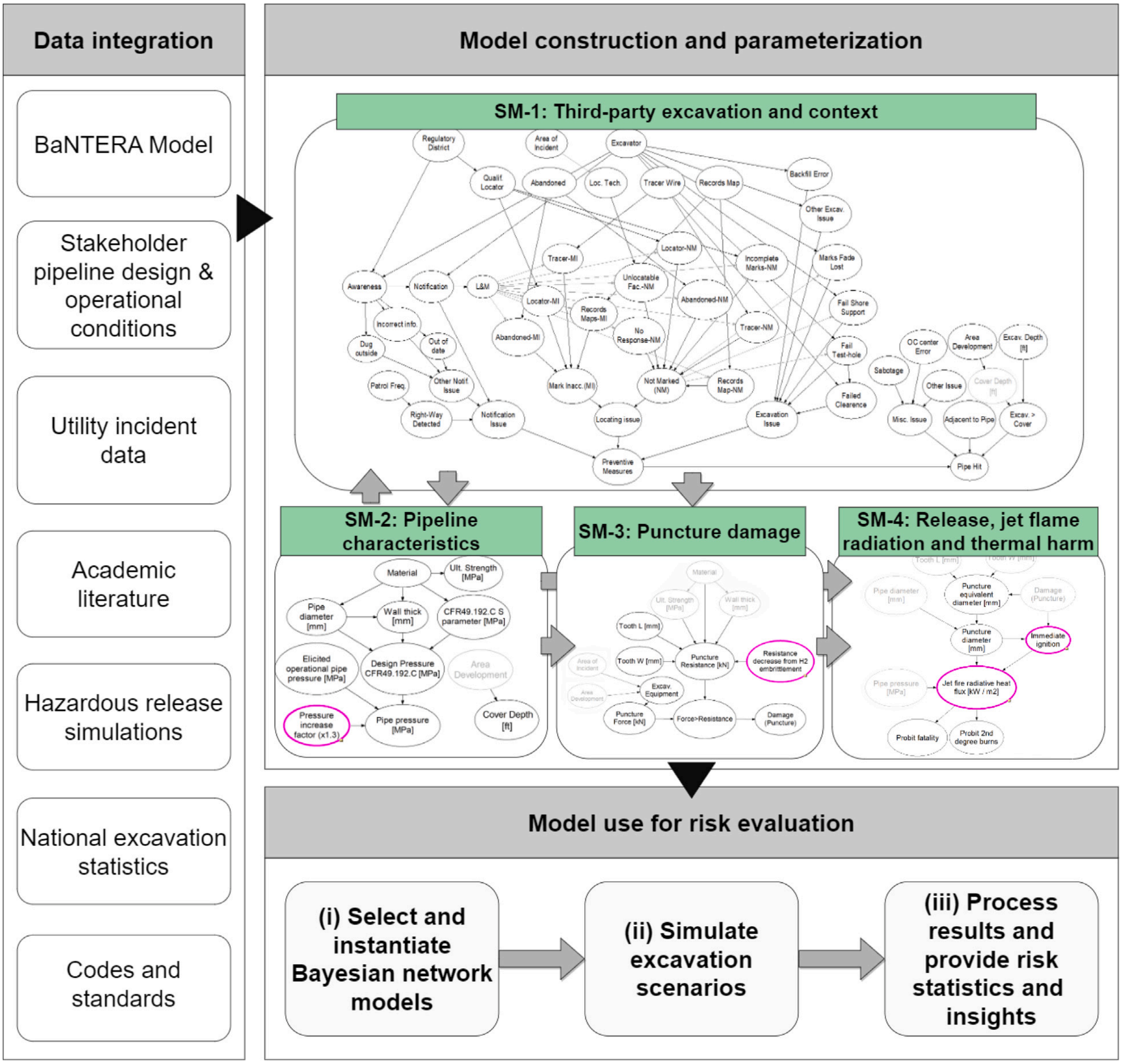


Fig. 1. Methodology used in this work for assessing the risk of TPD to natural gas pipelines transporting hydrogen.

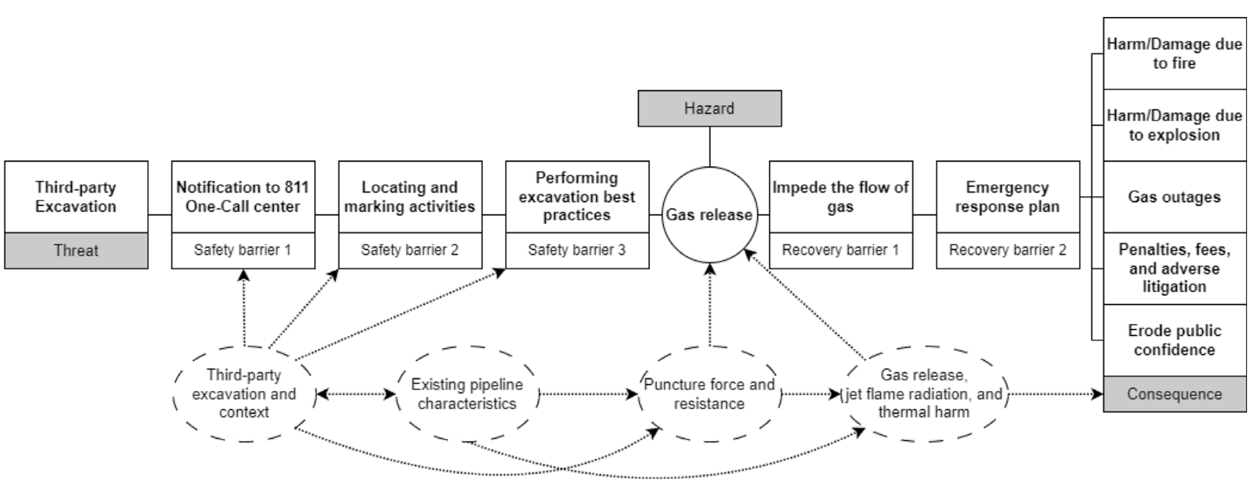


Fig. 2. Bow-tie diagram of third-party excavation damage. The bow-tie's barriers and hazard will depend on a number of interacting variables, as shown by the dashed nodes and arcs in the figure.

1. *Sub-model 1 (SM-1): Third-party excavation and context.* This sub-model includes the variables that affect the excavation process and the safety barriers recommended by CGA [14] and PHMSA [45]. These variables describe the excavation environment and the actors involved. The environment consists of the site characteristics (e.g., soil type, pipe depth, and area development) and the legal & regulatory context (e.g., mandatory or voluntary notifications to one-call centers). The actors comprise the third-party excavators (e.g., professionals or the general public), utility managers (e.g., utility companies and locating and marking contractors), and the one-call center (e.g., online submission or calling 811). These variables influence the adequacy of safety measures taken on an excavation (i.e., notification, locating and marking activities, and excavation practices) and the probability of a pipe hit. This sub-model was based on the BaNTERA model.
2. *Sub-model 2 (SM-2): Existing pipeline characteristics.* This sub-model includes the variables that define the gas pipelines' design and operation. These variables include pipe materials (e.g., API 5L steels, cast iron, and polymers), pressure (e.g., maximum allowable and operating pressure), geometry (e.g., diameter and wall thickness), and depth of cover (which depends on site development). These variables determine a pipeline's puncture resistance and gas release characteristics. This sub-model was based on PHMSA's mileage and facility records, expert opinions from a utility and GTI Energy, and the codes and standards described in Section 2.1.
3. *Sub-model 3 (SM-3): Puncture force and resistance.* This sub-model includes the variables that affect the puncturing of an underground pipeline. Puncture force depends on the excavation equipment, its exerted force, and its tooth geometry. Puncture resistance depends on the pipeline's ultimate strength, toughness, and hydrogen embrittlement. These variables influence the probability of a puncture and the gas release size when a pipe is hit in an excavation activity. This sub-model was based on the BaNTERA model, previous work by GTI Energy, and academic literature on hydrogen embrittlement.
4. *Sub-model 4 (SM-4): Gas release, jet flame radiation, and thermal harm.* This sub-model includes the variables that determine gas release characteristics and subsequent jet flame consequences. These variables are the release size, mass flow, ignition probability, radiative heat flux from a jet fire, and the probability of burns and death from thermal exposure. These variables influence the ignition and thermal harm probability. This sub-model was based on hazardous release simulations with HyRAM+.

The four sub-models above were initially created as Bayesian networks to capture the causal factors relevant to each facet of the problem. Then, we integrated each of the models, creating our final TPD risk model that captures dependencies between the sub-models. We call this model SHyTERP: Safe Hydrogen Transportation and Excavation Risk Prevention for Pipelines. Since the variables above vary depending on the pipeline system (distribution or transmission) and gas type (natural gas or hydrogen) studied, we created specific models for each of these cases. Therefore, four versions of SHyTERP were created in total, each of which described TPD for hydrogen transmission, hydrogen distribution, natural gas transmission, and natural gas distribution pipelines (i.e., 4 models and 16 sub-models were created in total).

The next section shows the modeling decisions used to parameterize each of the sub-models above and their dependencies.

3.2. Model parameterization

We made several modeling decisions to parameterize the variables in sub-models 1–4. We used the same parameterization for variables related to a third-party excavation activity, as in our previous work on the BaNTERA model [15]. We assumed that an excavation process with natural gas pipelines is similar to one with hydrogen pipelines. That implies the safety barriers in the bow-tie diagram of Fig. 2 and the variables in sub-model 1 are the same as those modeled in BaNTERA. However, this is not true for hazardous releases and thermal harm consequences in a hydrogen setting. Therefore, we made the following modeling decisions for sub-models 2–4[1]:

3.2.1. Puncture resistance and hydrogen embrittlement

Puncture is driven by a ductile failure that involves the plastic deformation of the pipe wall area in contact with the excavation equipment tooth, the generation of a failure on the inside surface of the pipe directly beneath the tooth, and the propagation of the failure through the pipe's wall until the penetration of the tooth. Brooker's model for puncture failure [46] has been proven as a suitable model for generating failure predictions in steel pipelines under multiple tooth geometries, pipeline designs, and material grades [15,25]. As such, this model was used to describe puncture failure in steel pipelines and is mathematically defined as:

$$R_p = 7.0074 \times 10^{-7} t(\sigma_u + 410.4)(L + 22.41)W(3.142 + W) \qquad \text{Puncture failure: } R_p < F \tag{2}$$

where R_p is a pipe's puncture resistance in [N], F the puncture load in [N] exerted by excavation equipment, t is the pipe wall thickness in [mm], σ_u is the ultimate stress of the pipeline material in [MPa], and L and W are a tooth's length and width, respectively, in [mm]. This model has been adapted in [25] to consider plastic pipelines by modifying the term $(\sigma_u+410.4)$ to $(\sigma_u+0.4)$ in Eq. (2). This modification implies that punctures in plastic pipes are expected to be 2 times more likely than in steel pipelines.

3.2.2. Hydrogen embrittlement

Hydrogen embrittlement is a major concern for using hydrogen on natural gas pipelines made of steel. Hydrogen molecules can dissociate on the inner surface of the pipeline, dissolve into the metal lattice, and alter its mechanical response to stress. Researchers have reported that hydrogen can negatively affect steel in both transmission and distribution systems. For instance, San Marchi and Somerday [17] showed that carbon pipe steels from API 5L Grade B to X80 had a significantly decreased reduction in area under tensile loads and a reduction of fracture toughness (50% on average) because of hydrogen. Similar results appear in other studies [19,20,47], which conclude that high-strength steels are more susceptible to hydrogen deterioration than low-strength steels. However, low-strength steels used for distribution mains are also sensitive to hydrogen action, as they show a significant decrease in impact toughness and brittle fracture resistance [21,22].

To the best of our knowledge, the effect of hydrogen on puncture resistance has not been studied extensively.The exact mechanisms of gaseous hydrogen embrittlement are not fully understood. While the effect on pipelines has not been determined precisely, it is known that embrittlement degrades mechanical properties and is an important factor to consider in risk modeling. Thus, despite the uncertainties surrounding the quantification of hydrogen embrittlement, it is highly important to include its effects as a factor in pipeline risk assessment models. Removing potentially relevant uncertain factors from a risk assessment also removes our ability to make effective decisions about those factor and how it contributes to potential risk differences. We believe it is still possible to make decisions even in the face of uncertainty, but only if we include and acknowledge these uncertainties rather than omitting them in a risk assessment model. Future research on hydrogen embrittlement can lead to reducing some of this uncertainty.

[1] All variables in these sub-models that are already present in BaNTERA are assumed to be parameterized as in [15] unless the following sections provide a different parameterization.

To account for the uncertainties surrounding the effect of hydrogen embrittlement on the puncture resistance of steel pipelines, we adopted a probability elicitation assessment from subject-matter experts at GTI Energy. Material science experts at GTI Energy suggested that hydrogen may affect punctures similarly to fractures on both distribution and transmission pipelines. As such, hydrogen embrittlement could reduce the plastic deformation associated with puncture failure and accelerate the crack propagation through the wall thickness at the location of the excavation equipment's tooth. These experts suggest that the reduction in puncture resistance caused by hydrogen embrittlement is multiplicative, and can be described by a probability distribution with the following percentiles: $1\%ile$: 0.1 reduction; $5\%ile$: 0.3 reduction; $50\%ile$: 0.55 reduction; $95\%ile$: 0.9 reduction. This means that the median decrease in puncture resistance caused by hydrogen embrittlement is expected to be of 0.55 (matching previous research by San Marchi and Somerday [17]). Therefore, in this preliminary risk model, the following linear multiplicative factor was used to account for the effect of hydrogen embrittlement on a pipe's puncture resistance:

$$R_{p,H_2} = HE \times R_p \qquad HE \sim Beta(5.3, 4.4) \tag{3}$$

where R_{p,H_2} is the puncture resistance of a metal pipeline in contact with hydrogen, HE is the multiplicative puncture resistance decrease factor accounting for uncertainties on the effect of hydrogen embrittlement, and $Beta()$ is the Beta probability distribution. HE was constructed with a Beta distribution matching the percentiles elicited from subject-matter experts at GTI Energy.

Brooker's model in Eq. (2) and its modified version in Eq. (3), were the center of sub-model 3 "puncture force and resistance" (see Section 3.1).

3.2.3. Operational conditions

In the U.S., natural gas pipelines are mostly underground and can be assumed to have a uniform gas temperature of 288.15 K (15 degC) and no heat transfer between the gas and the surrounding soil (i.e., isothermal flow is assumed) [7]. Operational pressures are very different between distribution and transmission systems. In this work, the following probability distributions were elicited from a utility company for an underground pipeline's operational pressure:

$$P_D \sim Triangular(0.11, 0.17, 0.51) \qquad P_T \sim Uniform(4.2, 8.4) \tag{4}$$

where P_D and P_T are the operational pressure, in MPa, of the U.S. distribution and transmission pipelines, respectively. Operational pressures are commonly lower than a pipeline's design pressure, which are determined by the pipe's material, diameter, and wall thickness [34]. To account for the dependency between pressure and a pipeline geometry, the design pressure dictated in the code CFR49.192.C [38] was also included in our model. Our model assumed that the operational pressure of a pipeline was equivalent to the minimum value between the pipeline's design pressure and a random sample from Eq. (4).

Replacing natural gas with hydrogen on pipelines could require adjusting the amount of hydrogen supplied to end users to match the energy content of natural gas. Hydrogen has a lower energy density than natural gas by volume (10,246 kJ/m^3 versus 33,906 kJ/m^3). Although hydrogen flows three times faster through pipelines than natural gas (three times faster according to Abbas et al. [48]), a 30% increase in operational pressure is still needed to deliver the same energy content as natural gas [16,29]. Therefore, we assumed that hydrogen pipelines would operate at 1.3 times the pressure of existing natural gas pipelines, on average. This 30% increase in operational pressure in a hydrogen setting matches with GTI Energy's simulations performed for the California Public Utilities Commission [16] using the `PipeEng` software [49] for a number of hydrogen transportation scenarios [16]. The sensitivity of the model's results to this parameter was assessed in Section 5.4.

A pipeline's geometry and operational pressure were the center of sub-model 2 "existing pipeline characteristics" (see Section 3.1).

Table 2
Immediate ignition probabilities for (a) natural gas and (b) hydrogen. Based on [52].

(a)		(b)	
Natural gas (Methane)		Hydrogen	
Mass flow, kg/s	Ignition probability	Mass flow, kg/s	Ignition probability
<1	0.007	<0.125	0.008
1–50	0.047	0.125–6.25	0.053
>50	0.200	>6.25	0.230

3.2.4. Gas release and ignition

We assume that punctures would produce a circular release with a diameter equal to the tooth area that punctures the pipe. As shown in our previous work for BaNTERA [15], a tooth length is assumed to be $L \sim Uniform(10, 150)$ mm, and the tooth width to be $W \sim Uniform(3, 20)$ mm. As such, a puncture equivalent diameter was assumed to range between 6.2 to 60 mm. If the tooth's equivalent circular diameter exceeds the pipeline's diameter in a simulated puncture, we assumed a full rupture of the pipe. Also, a discharge coefficient of 1.0 was assumed for conservatism.

We modeled the gas release as an isentropic process with constant pressure inside the pipeline and constant outlet temperature [50]. We used methane (CH_4) to represent natural gas. We calculated the steady-state mass flow from a simulated release using HyRAM+ [30]. The calculation depends on the simulated pipeline's pressure, diameter, and release size obtained from sub-models 1–3 described in Section 3.1. We correlated the calculated mass flow to an immediate ignition probability according to Tchouvlev et al. [51], as shown in Table 2. We do not consider mass flow adjustments due to potential crater formation.

Even though static electricity buildup and discharge is a known ignition hazard in releases from plastic pipelines [26], its effect on ignition probability was not considered in this work.

Release sizes and ignition probabilities were included in sub-model 4, "gas release, jet-flame radiation, and thermal harm" (see Section 3.1).

3.2.5. Thermal harm and loss

We modeled jet fires from ignited releases as perpendicular to the pipeline's right-of-way. We calculated the thermal radiation (measured as radiant heat flux) at every meter along a radial line of 202 m from the ignition source. This distance corresponds to the CFR49.192.5 [38] definition of location areas for risk assessment purposes. We measured the thermal radiation at a height of 1.5 m from the gas release source. This height assumes that pipelines are buried between 0.3–1.2 m [25], and that the jet fire at 1.5 m could reach an individual. We used 1.5 m as a conservative height for flame contact, even though pipelines can be buried deeper underground. We evaluated the thermal radiation at every possible location of an individual within a radius of 202 m from a jet fire and summarized it as a probability distribution based on simulations from HyRAM+.

We used HyRAM+ to calculate the thermal radiation assuming the Yuceil/Otugen notional nozzle model [30], relative humidity of 0.89, and release pressure and size simulated from sub-models 2 and 3 described in Section 3.1.

We used the Tsao & Perry probit model for 2nd-degree burns and fatalities to calculate thermal harm and loss for jet fire consequences, as suggested by LaChance et al. [52]. Thermal harm depends on the thermal dose unit (V), which combines the heat flux intensity, I, and exposure time, t, and is mathematically represented as follows:

$$V = I_{contact}^{4/3} \times t \tag{5}$$

where $I_{contact}$ is the radiant heat flux (W/m^2) from a jet fire, and t is the exposure duration in seconds. We used $t = 20$ s of thermal exposure based on recommendations from the Dutch Decree on the External Safety of Pipelines (BEVB) and previous QRAs for hydrogen pipelines [6]. The probit equations for fatalities and 2nd-degree burns are:

$$\begin{aligned} \text{Fatality}: \; Y_{thermal\ harm} &= -36.38 + 2.56 \times \ln(V) \\ \text{2nd-Degree Burns}: \; Y_{thermal\ harm} &= -43.14 + 3.0186 \times \ln(V) \end{aligned} \tag{6}$$

The result of Eq. (6) was used to calculate the probability of thermal harm ($P_{thermal\ harm}$) as follows:

$$Pr_{thermal\ harm} = F(Y_{thermal\ harm} \mid \mu = 5, \sigma = 1) \tag{7}$$

where $F(\bullet)$ is the normal cumulative distribution function. The radiant heat flux from a jet fire and associated probability of thermal harm and loss were included in sub-model 4, "gas release, jet-flame radiation, and thermal harm" (see Section 3.1).

3.3. Model use for risk evaluation

We applied SHyTERP and the causal inference methods described in Section 2.2 to assess the risk of TPD and identify the factors that affect the safe transportation of hydrogen through natural gas pipelines. The following steps were performed to simulate scenarios and evaluate risk:

i. First, we selected the appropriate SHyTERP version for the scenario, considering the type of pipeline (distribution or transmission) and the type of gas (natural gas or hydrogen). Then, we selected a suitable causal inference method that determined whether the scenario involved an associative, intervention, or counterfactual query (see Section 2.2). Finally, we instantiated the SHyTERP model based on the specific scenario and causal inference method (i.e., instantiated variables' states in the Bayesian network).
ii. Second, we ran 10 million Monte Carlo simulations using `pysmile` on the instantiated SHyTERP model. Each simulation represents a third-party excavation activity representing the scenario being studied. We recorded the simulation results for punctures, ignited releases, and thermal harms to obtain non-parametric probability distributions for these outcomes.
iii. Finally, we processed the distributions obtained in the previous step to generate useful statistics and insights about the risk of the scenario being studied. These included cumulative distributions and minimum, maximum, and average values on any variables of interest, among others.

The next sections present the different versions of the SHyTERP models and the risk assessment results obtained by following the aforementioned process.

4. Results

4.1. Risk model for third-party damage

The SHyTERP model proposed in this work is made up of four dependent sub-models (see Section 3.1). Each sub-model is a BN with variables that represent different aspects of a third-party excavation process, pipeline operational context, gas release, and its consequences. Fig. 3 shows these BNs. Four variables (shown as pink nodes in Fig. 3) depend directly on the type of gas transported through the pipelines, indicating how either hydrogen or natural gas affects the pipeline's pressure, puncture resistance, ignition probability, and jet flame characteristics. The dependencies between variables in different sub-models are shown as dashed nodes and arcs in Fig. 3. Also, as explained in Section 3.1, the proposed risk model had four versions: two for hydrogen transportation and two for natural gas transportation, each parameterized information specific for distribution or transmission pipelines. The variables "Pressure increase factor" and "Resistance decrease from H2 embrittlement" are only present in models describing hydrogen transportation. A list of the model's variables and parameterization sources are shown in Appendix A.

Table 3 summarizes the network characteristics of the proposed SHyTERP model and the sub-models comprised in it. Sub-model 1 was the largest and most complex sub-model, containing 67% of the variables and 68% of the dependencies in the risk model. Sub-model 2 "pipeline characteristics", was the most influential sub-model, as it connects to all other sub-models. The risk model for TPD is highly complex and comprehensive, with 73 variables and 110 conditional probabilities that capture a third-party excavation activity and its possible consequences.

4.2. Hydrogen outcomes and model validation

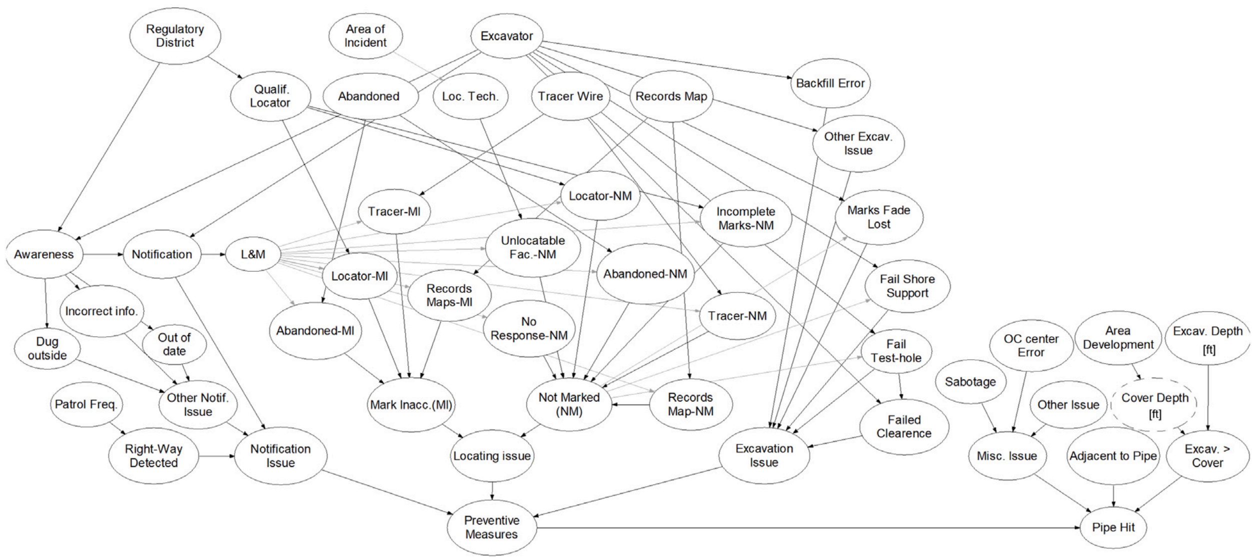
We applied the SHyTERP model for hydrogen pipelines by using the simulation process described in Section 3.3. Tables 4 and 5 (see 100% H_2 columns) show the average, minimum, and maximum values of the simulation results. Fig. 4 shows the cumulative distribution function (CDF) of each simulation for pipeline puncture, immediate ignition, 2nd-degree burns, and fatality from jet fires.

Table 4 indicates that, on average, hydrogen distribution pipelines are expected to be punctured 2.84 times per 1000 third-party excavations. Of these punctures, 5.32×10^{-2} ignite immediately and produce a jet fire, and 2.67×10^{-4} could cause a fatality. In comparison, Table 5 indicates that hydrogen transmission pipelines are expected to be punctured, on average, 1.55 times per 1 million third-party excavations. Of these punctures, 0.13 ignite immediately and produce a jet fire (due to higher release rates from transmission pipelines), and 2.24×10^{-2} could cause a fatality.

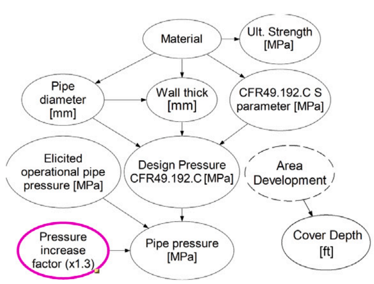
These results suggest that distribution pipelines have a higher frequency of ignited releases than transmission pipelines because of their higher susceptibility to puncture damage. However, transmission pipelines have a higher probability of immediate ignition than distribution pipelines due to higher release rates. The same trends were observed for 2nd-degree burns and fatalities caused by jet fires. The CDFs in Fig. 4 show that the uncertainty ranges for hydrogen ignitions and thermal harm are wide for both types of pipeline systems, so these events are expected to be rare (based on the simulated 50th percentiles).

The SHyTERP model for natural gas distribution pipelines was validated against U.S. performance measures and statistics from PHMSA for 2010–2020 [45]. Validation was difficult because the model is highly complex, and nationwide data on pipeline risk is limited to incidents with significant consequences, which are a small subset of the daily events in the U.S. pipeline system. Moreover, excavation damage data is more comprehensive and consistent for distribution pipelines than transmission pipelines [53]. Also, considering there is yet no operational data on hydrogen pipelines in the U.S., the proposed SHyTERP model could only be validated for natural gas distribution pipelines. Assuming an average of 20 million unique third-party excavations per year in the U.S. (based on CGA's one-call notification statistics [35]), Table 6 shows the validation results for the model.

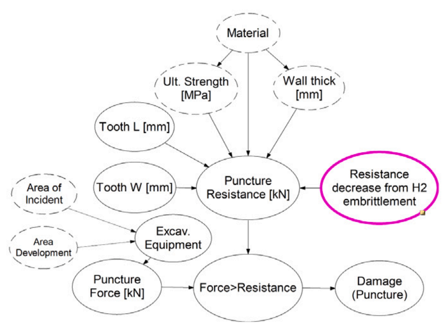
Table 6 shows that SHyTERP conservatively matched PHMSA's performance measures and statistics for the U.S. natural gas distribution system. The model estimated a lower expected number of damages per 1000 tickets (predicted: 2.52, PHMSA data: 3.10), so the model results in an estimated number of damages which is 81% the current U.S. statistic. However, our model only simulates punctures, while other damage (such as dents and gouges) are possible in an excavation, some of which lead to delayed failure. While PHMSA collects statistics on the number of third-party excavation damage events, PHMSA does not further subdivide this into the specific types of damage (e.g., puncture vs. gouge vs. dent). Punctures are widely considered by PHMSA as the prevalent failure mode in excavation activities, and is commonly used as a target variable in risk assessments [23], recognizing it is not a



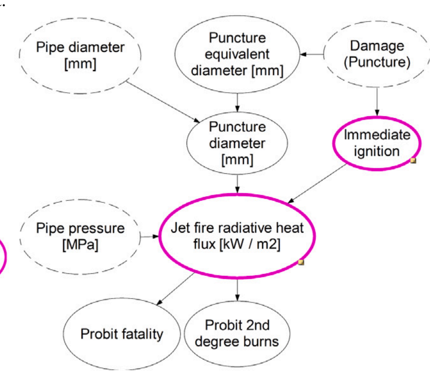
(a) Sub-model 1: Third-party excavation and context.



(b) Sub-model 2: Existing pipeline characteristics.



(c) Sub-model 3: Puncture force and resistance.



(d) Sub-model 4: Gas release, jet flame radiation, and thermal harm.

Fig. 3. The proposed SHyTERP model for assessing the risk of TPD to natural gas pipelines transporting hydrogen. SHyTERP consists of the four dependent sub-models shown above. Each sub-model has a version specific to the pipeline system and the gas type. The nodes "Pressure increase factor" and "Resistance decrease from H2 embrittlement" are only present in the models describing hydrogen transportation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Summary of the Bayesian network characteristics of sub-models 1–4. # Variables and # dependencies are the numbers of nodes and arcs in each network, respectively. # Dependencies across SMs are the number of arcs from one sub-model (row) to another (column).

Sub-model (SM)	# variables	# dependencies	# Dependencies across SMs			
			SM-1	SM-2	SM-3	SM-4
SM-1: Third-party excavation and context	49	75	–	3	1	0
SM-2: Existing pipeline characteristics	10	11	1	3	–	2
SM-3: Puncture force and resistance	8	7	0	–	0	4
SM-4: Gas release, jet flame radiation and thermal harm	6	5	0	0	0	–
Third-party damage risk model (overall)	**73**	**110**				

Table 4
Average, minimum, and maximum simulated values for distribution pipelines transporting natural gas (100% CH_4) and hydrogen (100% H_2).

	Distribution pipelines (average, min, max)		
	100% CH_4 (per excavation)	100% H_2 (per excavation)	μ_{H_2}/μ_{CH_4}
$Pr(Puncture)$	2.73×10^{-3} $(2.24\times10^{-3},\ 3.25\times10^{-3})$	2.84×10^{-3} $(2.34\times10^{-3},\ 3.40\times10^{-3})$	1.04
$Pr(Ignition)$	1.99×10^{-5} $(0.00,\ 6.97\times10^{-5})$	1.51×10^{-4} $(2.99\times10^{-5},\ 2.89\times10^{-4})$	7.60
$Pr(Burn)$	8.57×10^{-8} $(0.00,\ 9.95\times10^{-6})$	1.48×10^{-7} $(0.00,\ 1.99\times10^{-5})$	1.73
$Pr(Fatality)$	4.22×10^{-8} $(0.00,\ 9.95\times10^{-6})$	4.03×10^{-8} $(0.00,\ 9.95\times10^{-6})$	0.95

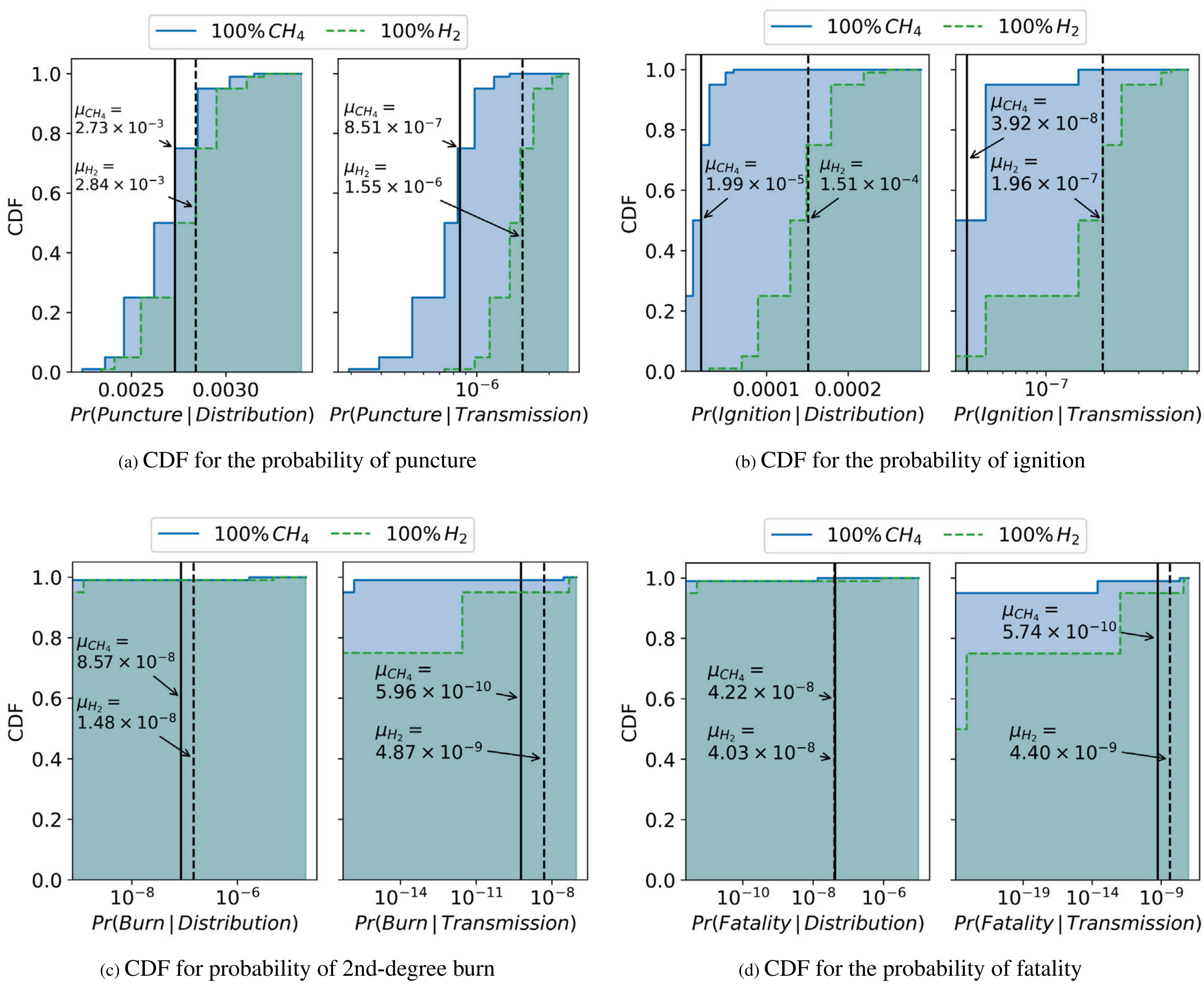
Table 5
Average, minimum, and maximum simulated values for transmission pipelines transporting natural gas (100% CH_4) and hydrogen (100% H_2).

	Transmission pipelines (average, min, max)		
	100% CH_4 (per excavation)	100% H_2 (per excavation)	μ_{H_2}/μ_{CH_4}
$Pr(Puncture)$	8.51×10^{-7} $(2.94 \times 10^{-7},\ 1.72 \times 10^{-6})$	1.55×10^{-6} $(7.35 \times 10^{-7},\ 2.4 \times 10^{-6})$	1.82
$Pr(Ignition)$	3.92×10^{-8} $(0.00,\ 2.45 \times 10^{-7})$	1.96×10^{-7} $(0.00,\ 5.39 \times 10^{-7})$	5.00
$Pr(Burn)$	5.96×10^{-10} $(0.00,\ 2.93 \times 10^{-8})$	4.87×10^{-9} $(0.00,\ 9.31 \times 10^{-8})$	8.17
$Pr(Fatality)$	5.74×10^{-10} $(0.00,\ 4.90 \times 10^{-8})$	4.40×10^{-9} $(0.00,\ 9.80 \times 10^{-8})$	7.67

Table 6
Validation of the proposed SHyTERP model for natural gas distribution pipelines.

Performance measure/statistic	PHMSA average 2010–2020	Proposed risk model (Average)
Excavation damages per 1000 tickets	3.10	2.52[a] (punctures)
Injuries per year	1.40	1.71
Fatalities per year	0.10	0.86

[a] The SHyTERP model can only simulate punctures, not all excavation damage types, and thus a slight underestimate vs. the PHMSA statistics is to be expected.



(a) CDF for the probability of puncture

(b) CDF for the probability of ignition

(c) CDF for probability of 2nd-degree burn

(d) CDF for the probability of fatality

Fig. 4. Simulated CDFs describing the risk of third-party excavation damage to natural gas pipelines transporting hydrogen.

perfect surrogate of the total observed statistics. The ShyTERP model showed a similar result for yearly injuries (considering 2nd-degree burns), being 1.2 times higher than PHMSA's statistics. The model's results for yearly fatalities are an oveestimate compared to PHMSA's statistics, but fall on the same order of magnitude. Future work should evaluate the sensitivity of the model to choices about the thermal harm model.

5. Case studies

In this work, we demonstrated the capabilities of the proposed SHyTERP model on four case studies designed to engage with stakeholders and discuss the use of hydrogen in natural gas pipelines and the risk posed by TPD. The studies were:

- *Case Study 1*: Compare the probability of TPD punctures, ignited releases, and jet fire thermal harm for hydrogen vs. natural gas.
- *Case Study 2*: Evaluate the effect of hydrogen on TPD risks for distribution systems comprised of different shares of plastic and steel pipes.
- *Case Study 3*: Evaluate the causes and consequences of past incidents in transmission pipelines had hydrogen been transported instead of natural gas.
- *Case Study 4*: Identify the most relevant causal factors affecting the risk of TPD and jet fire thermal harm on hydrogen pipelines.

The results of these case studies are shown below.

5.1. Case study 1: Compare the probability of TPD punctures, ignited releases, and jet fire thermal harm for hydrogen vs. natural gas

To provide a comparison of TPD risk for hydrogen vs. natural gas transportation through the current pipeline system, the model's results for natural gas are shown in Tables 4 and 5 (see 100% CH_4 columns), and Fig. 4.

Table 4 compares distribution pipelines for the two gases and shows that punctures, burns, and fatalities have similar expected probabilities. However, hydrogen pipelines were 7.6 times more likely to have immediate ignitions than natural gas pipelines. Despite this, hydrogen jet fires were found to be less fatal than natural gas ones. This result could be attributed to hydrogen jet fires having, overall, less radiative emissive power compared to natural gas jet fires [8]. Regarding the resulting CDFs, Fig. 4 shows that hydrogen distribution pipelines could have higher risks compared to natural gas pipelines, as their CDFs for punctures, ignitions, and thermal harm were shifted to the right (i.e., higher probability). For instance, Fig. 4d shows that hydrogen incidents could cause more fatalities than natural gas incidents, as a fatality was probable in up to 5% of the simulated excavations for hydrogen distribution pipelines, compared to less than 1% for natural gas distribution pipelines.

Table 5 shows that hydrogen transportation through transmission pipelines had consistently higher TPD risks than natural gas. A key finding was that the increase in thermal harm in hydrogen transmission pipelines could depend more on the increased frequency of ignited releases than on the additional puncture failures caused by hydrogen embrittlement. This is supported by Fig. 4a and b. Fig. 4a shows that hydrogen transmission pipelines had a 1.40 to 2.50 times higher puncture probability than natural gas pipelines across all percentiles of the simulated excavations (with a mean of 1.82 as shown in Table 5). In contrast, Table 5 shows that ignited releases were expected to be 5.0 times more probable in a hydrogen setting. Moreover, Fig. 4b shows that ignited releases were probable in less than 50% of the simulated excavations for natural gas pipelines, but in 95% for hydrogen pipelines.

5.2. Case study 2: Evaluate the effect of hydrogen on TPD risks for distribution systems comprised of different shares of plastic and steel pipes

Most U.S. utilities have a heterogeneous share of plastic and steel distribution pipelines, and in some regions, work is being carried out to transform their systems to fully plastic to the extent possible. However, plastic pipelines are more prone to getting punctured in excavation activities. As such, we sought to understand how injecting 100% hydrogen into a distribution system could increase the risks posed by TPD.

To inform this inquiry, an intervention analysis (see Section 2.2) was performed by estimating the effect of injecting pure hydrogen on a distribution system composed of different shares of plastics and steel. A total of 11 different percentage shares of materials were studied. The intervention queries, Q, to be solved with SHyTERP were expressed as follows:

$$Q = Pr(C = Yes \mid do(Material = \{Plastic = p,\ Steel = 100\% - p\}))$$
$$C = \{Puncture,\ Ignition,\ Fatality\} \quad (8)$$
$$p = \{0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100\}\ \%$$

Following the simulation process of Section 3.3, the results obtained in this intervention analysis are shown in Fig. 5 for the probability of punctures, ignitions, and fatalities caused by jet fires.

Fig. 5(a) shows that carbon steel distribution pipelines had lower puncture probabilities than plastic ones, regardless of the gas being transported. A key question was how hydrogen embrittlement would affect steel pipelines, but our results showed that the difference in punctures between natural gas and hydrogen distribution pipes was only 3.7 per 10,000 excavations. Moreover, it should be noted that the uncertainty range for steel hydrogen pipelines was narrower than for natural gas, as hydrogen pipes are expected to operate at 30% higher internal pressure (see Section 3.2), which will require narrower ranges of wall thickness and diameters. Furthermore, the difference in punctures was not significant for distribution networks with up to 70%/30% share of plastic and steel pipes (similar to the current U.S. distribution system), for both expected values and uncertainty ranges.

Fig. 5(b) shows that hydrogen pipelines had consistently higher immediate ignition probabilities than natural gas pipelines, especially for steel systems, as hydrogen embrittlement and higher ignition probability add up. Fig. 5(c) shows that fatalities from those ignited releases were improbable and similar for both gases regardless of the material shares. Additionally, reduced probabilities of fatalities were observed for natural gas systems with more than 80% steel pipes because of steel's inherent higher resistance to punctures and lower ignition probability. This reduction was not present for hydrogen systems, which could be attributed to hydrogen's significantly higher ignition probability. The minimum and maximum values obtained for fatalities in the simulations were wide, ranging from 0 to 10^{-5} for both gases. Therefore, we can only conclude that fatalities are expected to be in the same order of magnitude for both gases.

5.3. Case study 3: Evaluate the causes and consequences of past incidents in transmission pipelines had hydrogen been transported instead of natural gas

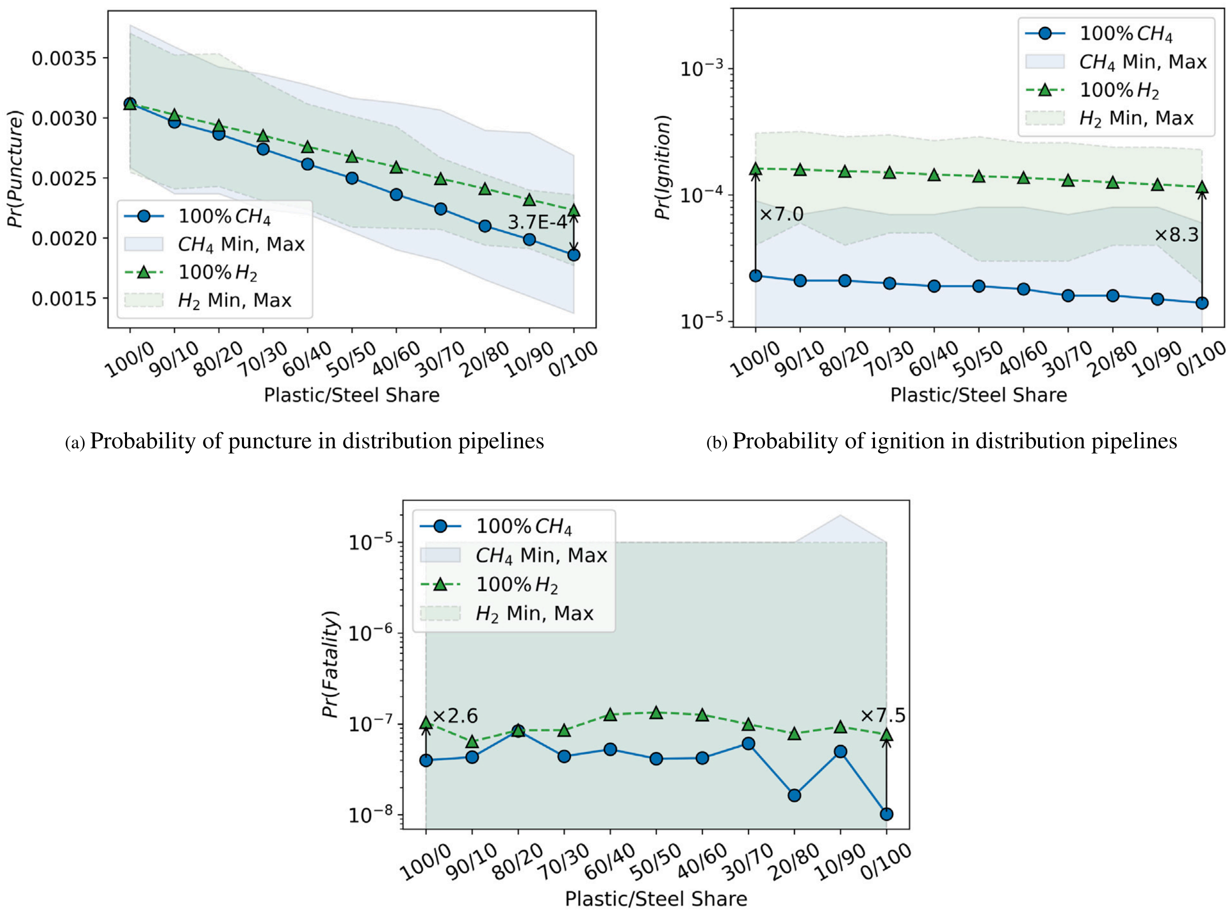
Excavation damages to transmission pipelines are infrequent. However, they can lead to catastrophic consequences if the pipeline is punctured and the released gas ignited. As such, a relevant insight towards assessing the risk of hydrogen transportation through existing transmission pipelines was to evaluate what could have happened in past incidents if hydrogen had been transported instead of natural gas.

To inform this inquiry, a counterfactual analysis (see Section 2.2) was performed on a utility company's incidents in 2020 and 2021. This analysis evaluated how transporting hydrogen could have impacted the probability of punctures and ignitions at the time of those events. The 19 incidents analyzed include 18 pipe hits, one puncture, and no ignited releases.

To perform the counterfactual analysis, the following steps were performed for each of the incidents:

1. For each of the studied incidents, do:
   - 1.1. Evaluate the prior probability of puncture and ignition conditioned on all evidence recorded in the event on the variables included in the proposed SHyTERP model. This prior probability will represent the moment just before the incident happens.
   - 1.2. Evaluate the following counterfactual queries, Q, following the simulation process in Section 3.3:

$$Q = Pr(C_{Gas=H_2} = Yes \mid C = No,\ Gas = CH_4,\ E = e)$$
$$C = \{Puncture,\ Ignition\} \quad (9)$$



(a) Probability of puncture in distribution pipelines

(b) Probability of ignition in distribution pipelines

(c) Probability of fatality in distribution pipelines

Fig. 5. Probability of puncture, ignition, and fatality caused by a jet fire in a distribution system for different shares of plastic and steel pipelines in both hydrogen and natural gas settings.

where $E = e$ is all evidence recorded in the event on the variables included in the TPD risk model.

2. Perform 10 thousand Bayesian bootstrapping [54] simulations on the aggregated results obtained in the previous step. The bootstrap results allow accounting for the uncertainty in the known population of past incidents in the utility's pipeline system.

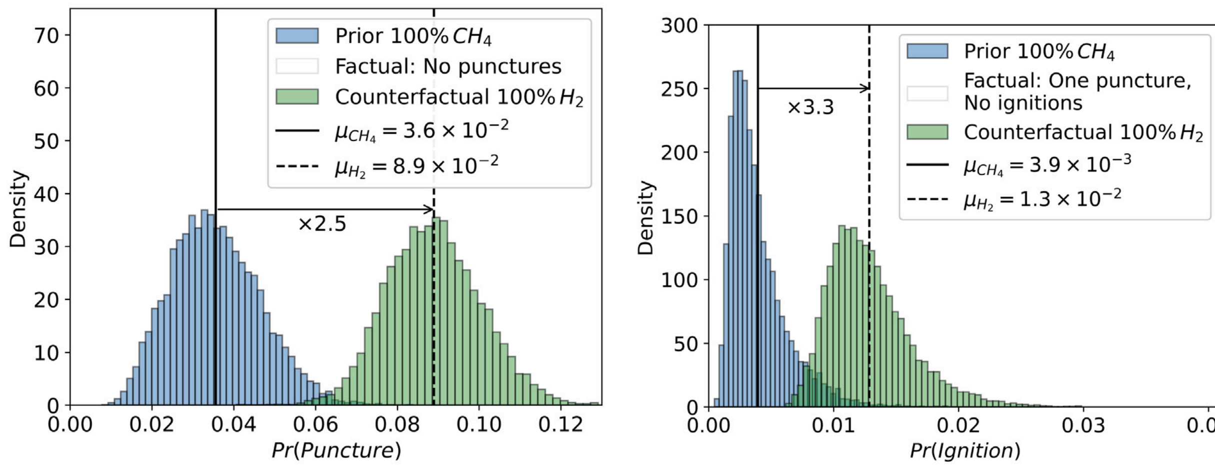
The resulting bootstrapped prior and counterfactual probabilities of punctures and immediate ignitions obtained through the aforementioned process are shown in Fig. 6.

Fig. 6(a) shows the prior probability distribution of puncturing a pipeline in the 19 studied incidents. The proposed SHyTERP model estimated the prior probability mean to be 3.6×10^{-2}, which is equivalent to predicting 0.69 punctures in the 19 incidents. Only one puncture was observed between 2020–2021, which supports the model's accuracy. The counterfactual probability of puncture for hydrogen in the same incidents was estimated to be 2.5 times higher (i.e., 8.9×10^{-2} punctures per excavation). Therefore, the counterfactual analysis shows that 2 punctures, instead of 1, could have been expected had hydrogen been transported through the pipelines between 2020–2021. Moreover, Fig. 6(a) shows that hydrogen could have increased the uncertainty range of puncture probability in the 19 incidents, as the lower bounds for hydrogen transportation match the upper bounds for natural gas transportation.

Fig. 6(b) shows the prior probability distribution of an ignited release in the 19 studied incidents. The proposed risk model estimated the prior probability mean to be 3.9×10^{-3}, or 0.074 expected ignitions in the 19 incidents. No ignitions were observed between 2020–2021, which supports the model's accuracy. The counterfactual probability of ignited releases for hydrogen in the same incidents was estimated to be 3.3 times higher (i.e., 1.3×10^{-2} immediate ignitions per excavation). Therefore, the counterfactual analysis shows that for the 2 potential punctures expected for hydrogen pipelines in the 19 incidents, there could have been a 25% probability of observing an ignited release. Furthermore, Fig. 6(b) shows that hydrogen could have changed both the location and scale of the probability distribution of ignited releases in the 19 incidents. The prior probability of ignition for natural gas was positively skewed, with a prior probability mode of 2.2×10^{-3}; an ignition was unlikely. However, the counterfactual probability of ignition for hydrogen could have been less skewed and have a mode counterfactual probability of 0.011; an ignition would not be unexpected.

5.4. *Case study 4: Identify the most relevant causal factors affecting the risk of TPD and jet fire thermal harm on hydrogen pipelines*

We performed a sensitivity analysis on the SHyTERP model to identify the most relevant causal factors affecting the risk of TPD and jet fire thermal harm on hydrogen pipelines. The target node for the sensitivity analysis was "Jet fire radiative heat flux" in sub-model 4 (see Fig. 3d). The most relevant causal factors are those variables that, by changing their marginal probabilities, will increase the probability of higher heat radiation from a hydrogen jet fire. This is because higher heat radiation is associated with higher probabilities of fatalities, ignitions, and larger



(a) Probability of puncture in past incidents

(b) Probability of ignition in past incidents

Fig. 6. Prior, factual, and counterfactual bootstrapped probabilities of puncture and ignition for past incidents in a utility partner's transmission system had hydrogen been transported instead of natural gas.

Table 7
Most relevant causal factors affecting the risk of TPD and jet fire thermal harm in hydrogen transmission and distribution pipelines.

(a) Most relevant causal factors affecting radiative heat flux in hydrogen distribution pipelines

100% H_2 distribution pipelines		
Rank	Variable	Relevance
1	Immediate ignition	1.00
2	Pipe pressure	0.57
3	Excav. preventive measures	0.53
4	Material	0.21
5	Wall thickness	0.12
6	Puncture force	0.11
7	Pipe diameter	0.10

(b) Most relevant causal factors affecting radiative heat flux in hydrogen transmission pipelines

100% H_2 transmission pipelines		
Rank	Variable	Relevance
1	Excav. preventive measures	1.00
2	H_2 embrittlement	0.72
3	Puncture force	0.68
4	Pipe pressure	0.53
4	Immediate ignition	0.53
5	Excavator tooth W	0.28
6	Wall thickness	0.25
7	Excav. equipment	0.24
7	Excavator tooth L	0.24

release sizes from punctures. The sensitivity analysis was based on Kjærulff and Van Der Gaag [55] sensitivity derivative parameter, S, for all the variables in the models for hydrogen transportation in both distribution and transmission systems. The sensitivity derivative parameter S of a BN's node state "$V_i = v$" given a target node state "$Y_i = y_i$" means that a change c on the value of $Pr(V_i = v_i)$ will cause a change of $S \cdot c$ on the value of $Pr(Y_i = y_i)$. Table 7 shows the sensitivity analysis results. Relevance is calculated with respect to the model's variable with higher sensitivity derivative parameter S, and the values are proportional to the parameter ranked first (i.e., Relevance = S_i/S_1, with $i = \{1, \dots, n\}$ for n ranked parameters). The variables included in Table 7 are only those whose S parameter was, at least, 10% of the higher-ranked variable.

Table 7a shows that the three most relevant causal factors affecting the risk of TPD on hydrogen distribution pipelines were "Immediate ignition", "Pipe pressure", and "Excavation preventive measures". These factors reflect that hydrogen has high ignition probabilities and potentially higher pressures to meet customer demand, which can increase the frequency and consequences of ignited releases and jet fires. Therefore, it is essential to improve TPD preventive measures during excavation. Pipeline "Material" was the fourth most influential factor. Distribution systems are mainly made of plastics, which have low puncture resistance. Therefore, "Material" suggests the need for more puncture-resistant materials, such as fiber-reinforced composites, which have better properties than common polyethylenes used for piping [56].

Table 7b shows that the three most relevant causal factors affecting the risk of TPD on hydrogen transmission pipelines were "Excavation preventive measures", "H_2 embrittlement", "and Puncture force". This result shows that preventing excavation damage becomes key in the integrity management of hydrogen transmission pipelines, as hydrogen embrittlement can significantly affect the pipeline's resistance to damage. Moreover, there could be a need to change the current excavation practices, as high-force excavators have become standard in excavation activities. For instance, horizontal directional drilling can exert twice as much puncture force on a pipeline as a traditional excavator [25]. Combined with the uncertainties of hydrogen embrittlement, horizontal directional drilling could be a high-risk practice compared to other excavation alternatives. Additionally, "Pipe pressure" and "Immediate ignition" were found to be equally relevant in the fourth place. These results highlight that embrittlement, higher pressures, and higher ignition probabilities can increase the frequency of ignited releases that could lead to high-consequence events and negatively affect the public perception of hydrogen.

For both distribution and transmission systems, causal factors in places 5–7 showed that the integrity management of hydrogen pipelines could highly benefit from understanding the puncture forces exerted by excavation equipment and the puncture resistance of pipelines.

6. Conclusions and future directions

Third-party excavation damage is a major threat to natural gas pipelines and a potential challenge to the safe transportation of hydrogen through existing infrastructure. This work presented a first-of-its-kind model, SHyTERP, to assess the risk of TPD in natural gas pipelines transporting hydrogen. We specifically focused on the risks of punctures, immediate ignitions, and jet fires in distribution and transmission systems.

The proposed SHyTERP model draws together causal factors, models, statistics, and validated physical models of hydrogen and natural gas release and jet flame behaviors. It incorporates 73 variables, 110 conditional dependencies, and the uncertainties involved in a third-party excavation process and its consequences, making it a comprehensive model of how these factors affect the physical hazard and the safety of both hydrogen and natural gas applications. A probabilistic simulation approach based on Bayesian networks was proposed to obtain relevant statistics and insights on the risk of TPD. This approach allowed us to validate the model against PHMSA's national historical data, showing that the model's average risk results for natural gas pipelines are consistent with these statistics. Moreover, the results for hydrogen pipelines were in line with current scientific knowledge of the topic, showing that embrittlement in transmission pipelines and high ignition probability can significantly increase the probability of punctures and jet fire scenarios. Furthermore, the SHyTERP's simulation approach to TPD risk allowed us to compare not only averages, but also the full changes in the probability distribution of punctures, ignitions, and jet flame consequences in both natural gas and hydrogen settings (see Fig. 4). These results showed that analysts should aim to reduce not only the expected number of undesired events but also the uncertainty of their occurrence.

The causal Bayesian network approach enabled us to identify the most relevant risk drivers and prevention insights for managing the integrity of future hydrogen pipelines. These insights, derived from the four case studies in Section 5, support the following recommendations to enhance TPD safety in future natural gas pipelines transporting hydrogen:

Distribution pipelines

1. The probability of ignited releases and jet fire events is expected to be significantly higher in distribution pipelines using hydrogen vs. those with natural gas. Therefore, we recommend that the first pilot projects for pure hydrogen pipelines should be done in remote or less-populated areas to enable a safer transition to hydrogen, and we further recommend conducting case-specific QRAs to demonstrate that hydrogen distribution meets tolerable risk levels.
2. The probability of punctures in steel pipelines was found to be slightly increased by hydrogen embrittlement. However, the total risk from hydrogen pipelines was found to be similar across different material shares in distribution systems. Therefore, there appears to be no advantage to avoiding steel pipelines in planning hydrogen distribution projects.

Transmission pipelines

1. Hydrogen injection into transmission pipelines was found to increase the risk of excavation damage significantly and consistently vs. natural gas pipelines. Therefore, we recommend that case-specific QRAs should be required to demonstrate that hydrogen transportation meets tolerable risk levels.
2. Excavation practices near underground transmission pipelines may need to be re-evaluated. The puncture force on potentially less resistant steel transmission pipelines could cause a significant increase in the risk of excavation damage. Therefore, we recommend the wider use of non-destructive vacuum excavation methods (see [57] for further details) and stricter excavation damage prevention practices when applicable. We also suggest avoiding high-risk excavation methods, such as horizontal directional drilling, before the effect of hydrogen embrittlement is better understood.

Besides the above recommendations, more research is needed to include hydrogen embrittlement in pipeline QRA models. Although many experimental works have been done, pipeline QRA still lacks proper adjustments for the possibility of hydrogen embrittlement in steel pipelines. Future QRA models should not assume that hydrogen pipelines have the same failure frequencies as natural gas pipelines until better guidelines for including hydrogen embrittlement are available. Until then, conservative modifications to failure probabilities, such as the one we made in this work, are essential to avoid ignoring the effects of hydrogen embrittlement on the probability of failures in pipeline QRAs.

This work's analysis and modeling approach provides a baseline for further QRA studies on the risk of TPD to natural gas pipelines transporting hydrogen. However, the following future work is needed on several aspects not considered in this study:

- First, SHyTERP's assumptions and parameterization should be revisited after more work becomes available on the effect of hydrogen embrittlement on puncture resistance and the need for increased pressure to satisfy current energy demands. This will enhance the precision of the model's simulations since most of the hydrogen information today is based on limited data.
- Second, for a better assessment of jet fires, future work should consider the effect of wind and crater formation on hazardous releases from excavation activities.
- Third, more detailed insights into the individual and societal risk of ignited releases could be pursued by generating risk profiles and transects on a specific set of pipeline designs and scenarios.
- Fourth, assessing the risk of delayed ignitions and explosions (in both confined and unconfined settings) is highly important for hydrogen pipelines, as hydrogen dispersion and flammable cloud formation differ significantly from natural gas. Therefore, future work should consider the effects of hydrogen regarding explosion and overpressure risks.
- Finally, future work should consider the effect of electrostatic buildup and discharge in plastic pipelines, as these could increase the risk of ignited releases in distribution systems transporting hydrogen.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This material is based upon work supported in part by the National Science Foundation, United States under Grant No. 2045519. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The authors would also like to acknowledge the support from the Marvin Roush Fellowship at the University of Maryland, United States. The technical support from Ernest Lever and Oren Lever at GTI Energy is also gratefully acknowledged.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ijhydene.2023.12.195.

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