Hazardous air pollutants in transmission pipeline natural gas: an analytic assessment

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Abstract
Natural gas production occurs in specific regions of the US, after which it is processed and transported via an interconnected network of high-pressure interstate pipelines. While the presence of hazardous air pollutants (HAPs) in unprocessed, upstream natural gas has been documented, little has been published on their presence in the midstream natural gas supply. We systematically evaluated publicly available, industry-disclosed HAP composition data sourced from Federal Energy Regulatory Commission (FERC) natural gas infrastructure applications submitted between 2017 and 2020. Natural gas composition data from these filings represent approximately 45% of the US onshore natural gas transmission system by pipeline mileage. Given that reporting natural gas HAP composition data is not required by FERC, only 49% of approved expansion projects disclosed natural gas HAP composition data. Of those applications that disclosed composition data, HAP concentrations were typically reported as higher for separator flash gas and condensate tank vapor compared to liquefied natural gas and transmission-grade natural gas, with mean benzene concentrations of 1106, 7050, 77, and 37 ppm respectively. We also identified one pipeline operator that reports real-time HAP concentrations for its natural gas at five pipeline interconnection points. Similar to the FERC applications, this operator reported benzene, toluene, ethylbenzene, xylenes and hydrogen sulfide as present in transmission pipeline natural gas. Notably, mercury was also reported as detectable in 14% of real-time natural gas measurements but was not reported in any FERC applications. Given that transmission infrastructure releases natural gas during uncontrolled leaks and loss of containment events as well as during routine operations (e.g. blowouts and compressor station blowdowns), these gas composition data may serve as a critical component of air quality and health-focused evaluations of natural gas releases.

1. Introduction
Natural gas production from fossil sources in the US has grown substantially, from 510 billion cubic meters in 2005–949 cubic meters in 2020 (US Energy Information Agency 2021). Natural gas production occurs in specific regions of the US, typically far from demand centers. After it has been produced and processed, natural gas is transported throughout the US using an interconnected network of high-pressure interstate transmission pipelines and supporting infrastructure. Despite its widespread use as an energy source, the chemical composition of natural gas throughout the natural gas supply chain is understudied. Although the climate impacts of methane emissions are clear (Saunois et al 2016, Fletcher and Schaefer 2019, Szopa et al accepted), without a detailed understanding of the composition of natural gas—and the variability of its composition across the natural gas supply chain and through time and space—it is challenging to evaluate the associated air quality and human health hazards, risks, and impacts when it is emitted—unburned—to the atmosphere.
While natural gas is composed predominantly of toxicologically inert methane, it also contains a diverse array of naturally occurring organic and inorganic compounds (Abelson 1994, Burruss and Ryder 2014, Faramawy et al 2016). Some of the associated non-methane volatile organic compounds (NMVOCs) are toxicologically inert with respect to human health, while others are well understood to be toxic, carcinogenic and/or teratogenic and classified as hazardous air pollutants (HAPs) under the Clean Air Act (United States Code 2021). These NMVOCs, including HAPs, have been detected in both natural gas sampled from natural gas production wells (DiGiulio and Jackson 2016) and the emissions of unburned gas at upstream natural gas wells, dehydrators, and other processing facilities (Warnke et al 2014, SAGE Environmental Consulting 2019, Garcia-Gonzales et al 2019). Further these compounds have been detected in the natural gas distribution system (Michanowicz et al 2022).

Unlike the upstream oil and gas production sector, there are no identifiable peer-reviewed analyses of HAPs in the natural gas transported by the US natural gas transmission system although one study identified multiple heavy metals in transmission pipeline natural gas in France (Cachia et al 2018). After upstream production, natural gas undergoes some degree of processing, typically at dedicated natural gas processing plants that then deliver the processed gas into the midstream transmission system. While there is a dearth of peer-reviewed studies on HAPs in natural gas within the transmission system, isolated reports indicate that HAPs are entrained in this gas. One report submitted to the US environmental protection agency (EPA) (EC/R Incorporated 2011) noted that the HAPs n-hexane, 2,2,4-trimethylpentane, and the benzene, toluene, ethylbenzene, and xylenes (BTEX) compounds could be found in transmission pipeline natural gas, but the methods and source details for the data were not provided. One sample taken by the South Coast Air Quality Management District (Southern California), described as taken from the inlet to a transmission pipeline, also reported n-hexane, benzene, and toluene in the sample (South Coast Air Quality Management District 2019).

The lack of peer-reviewed studies on gas composition in transmission pipelines likely reflects, at least in part, the difficulty in researcher access to the gas stream within transmission infrastructure. Transmission pipelines and associated facilities are considered critical infrastructure and not accessible to the public. Additionally, transmission facilities that might emit HAPs through natural gas releases also generally burn natural gas, so HAPs present in combustion emissions would commingle and interfere with the sampling of HAPs from unburned natural gas emissions in ambient air near those facilities.

Regulatory filings for natural gas transmission infrastructure projects provide an alternative data source on the composition of natural gas. Natural gas transmission projects, including interstate pipelines and liquefied natural gas (LNG) facilities, must apply for and receive authorization from the Federal Energy Regulatory Commission (FERC) prior to construction (United States Code 2021). The FERC application includes an environmental report on air quality impacts, which FERC recommends also include the HAP composition profile for natural gas released by a transmission facility during routine operations such as fugitive emissions (Federal Energy Regulatory Commission, Office of Energy Projects 2017). HAP composition data may also be included for separator flash gas emitted when suspended pipeline condensate liquids at high pipeline pressures are transferred to lower atmospheric pressures and partially volatize, pipeline condensate liquids, and vapors from tanks storing pipeline condensate liquids (figure 1).

By analyzing publicly available pipeline industry data, this is the first peer-reviewed study to identify and estimate the concentration of HAPs in natural gas within the US transmission pipeline system. Given that natural gas infrastructure releases natural gas during both routine operations and off-normal loss of containment events (e.g. blowdowns and blowouts), these composition data can support future air quality and health-focused evaluations of natural gas transmission infrastructure emissions.

2. Methods

2.1. Project identification, search strategy, and unit conversions

In order to compile a dataset of gas composition reflective of currently operating interstate pipelines and associated infrastructure, we selected projects for analysis if they had received final FERC approval, as noted on the list of approved natural gas transmission projects maintained by FERC, during the years 2017 through 20204. We reviewed all approved project applications, including LNG projects, except those that involved the sale or abandonment of a pipeline. It should be noted that the approved project list was reorganized by FERC midway through our assessment and several projects were removed. However, we verified that these project applications had in fact been awarded a Certificate and so we retained them in the study. We searched for HAPs in both natural gas and any other associated pipeline gases and liquids.

We utilized a manual search strategy for projects that included an operational emissions appendix for Resource Report 9, detailing air and noise impacts, in the application environmental reports. We conducted

4 Available at https://ferc.gov/industries-data/natural-gas/approved-major-pipeline-projects-1997-present.
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Figure 1. Sources of HAPs at transmission pipeline compressor stations from non-combustion sources. Emissions can result from (A) blowdowns (discrete releases that evacuate natural gas from compressor stations and pipelines), (B) emissions from pipeline liquid condensate tanks, and (C) flashing when HAPs volatilize from the liquid to the gas phase as they move from high pipeline pressures to atmospheric pressure. Natural gas fugitive emissions are also emitted by leaks at valves, flanges, and other above-ground pipeline components (not shown). Photographs are of a transmission pipeline natural gas compressor station in Weymouth, MA.

a secondary screen by searching FERC eLibrary dockets containing electronic collections of all filings associated with a project application using individual HAP keywords to identify docket filings of interest and then further searched within those documents (see supplemental figure S1 for an example search result). Docket search terms included ‘hexane’ and ‘benzene’ since those appeared frequently, and occasionally as the only HAP reported in a project application. HAPs evaluated for the analysis included hexane, benzene, toluene, ethylbenzene, total xylenes, 2,2,4-trimethylpentane, and hydrogen sulfide. Naphthalene and cumene were reported as present in the natural gas for only one project and therefore we excluded these compounds from our analysis. No other HAPs were identified through our docket search.

HAP concentrations in FERC project applications were typically reported as weight percent or mole percent. We converted units to parts per million (ppm) by volume in a hierarchical fashion that minimized the use of underlying assumptions (see supplemental information and supplemental table S1).

2.2. Geographic region and pipeline mileage analyses

We categorized projects geographically using the project’s location taken from the FERC approved project list within US Energy Information Administration (EIA) interstate pipeline market regions (US Energy Information Agency 2007). The EIA regions are based upon flows of gas, and therefore the gas composition data derived from an application could be considered representative of that market region. For most data points, the relevant project fell entirely within one EIA region. In a few cases, the project spanned multiple regions. If the data source could be attributed to a single facility, then that facility was taken as the geographic region (e.g. natural gas composition data that were attributed to a specific compressor station in a given EIA region, even though construction on the project may have spanned into another region). For four projects, the data were attributed to multiple facilities in different regions and could not be assigned to a single region. Those data were excluded from the geographical analysis.
Pipeline mileage was calculated as described in the supplemental information using data from the US Pipeline and Hazardous Materials Safety Administration (2022).

2.3. Real-time transmission pipeline HAP data

Many transmission pipeline operators provide non-HAP composition data for NMVOCs in their natural gas on an ‘informational postings’ web page. As such, we also reviewed those informational postings sites for each pipeline operator in the FERC analysis for HAP composition data. One operator posted real-time gas chromatography data for natural gas delivered at interconnection delivery points involving five interstate natural gas transmission pipelines, each of which had also submitted one or more applications to FERC during the study period. Interconnect points were located in or around Fort Bend county, immediately southwest of Houston Texas. Reported natural gas composition data included methane, alkanes from ethane through pentane, hexanes plus fraction, total and individual aromatics, mercury, and hydrogen sulfide. Data were downloaded for a 7 month period (1 December 2020 to 1 July 2021; see supplemental information methods) for each of the five pipelines and natural gas from one storage facility. According to the operator’s informational postings site, natural gas samples were collected and processed using Gas Processors Association methods GPA2166, GPA2198, and GPA2261. Reported data could not be independently verified.

2.4. Statistical analysis

We used nonparametric statistics for hypothesis testing due to low sample sizes and/or data deviating from the normal distribution. Descriptive statistics for real-time pipeline measurement data were calculated by bootstrapping in R (version 4.0.2) with sample size n = 5000 as the distribution of HAP concentrations tended to follow a log-normal distribution. We tested associations between project factors (year of application filing, geographical location, addition of pipeline mileage, and addition of compressor station capacity) and whether the project reported HAP composition data by logistic regression analysis. Descriptive statistics and logistic regression were calculated using the Jamovi interface for R, version 1.8.1.

3. Results

3.1. Frequency of HAP disclosures for natural gas composition

Out of all approved transmission projects in the study period, we found that 51% of projects did not report any natural gas HAP composition data. For projects that reported natural gas HAP composition, hexane concentrations were reported most frequently (44% of all approved projects) followed by the BTEX compounds (30%, 25%, 17%, and 23% respectively), 2,2,4-trimethylpentane (2,2,4-TMP, 13%), and hydrogen sulfide (7%; see figure 2). For those projects that did report HAP concentrations, individual HAPs were reported as present in 58% (hydrogen sulfide) to 90% (hexane) of applications.

Conversely, the proportion of all approved projects that reported a given HAP as being not present in its natural gas was low and ranged from 4% (2,2,4-TMP) to 9% (ethylbenzene). It was not possible to determine whether missing data indicated an absence of HAPs in a project’s natural gas or that the data were simply not reported.

3.2. Quantification of reported HAP concentrations in transmission pipeline natural gas and associated HAP sources

Mean concentrations reported for transmission pipeline natural gas ranged from 1 ppm for hydrogen sulfide to 114 ppm for hexane (table 1 and figure 2), with maximum values up to 450 ppm for hexane and 299 ppm for benzene. Mean concentrations reported in natural gas for the BTEX compounds were 37, 19, 3, and 11 ppm respectively. BTEX concentrations were considerably higher for separator flash gas (1106, 1508, 96, and 856 ppm respectively) and condensate tank vapor (7050, 7155, 668, and 4226 ppm respectively). Unlike natural gas, some projects reported high concentrations of hydrogen sulfide for separator flash gas (mean 5134 ppm) and condensate tank vapor (3320 ppm) although the number of observations were small (n = 4 and n = 5, respectively). LNG facility natural gas prior to processing and liquefaction was more similar to pipeline natural gas, with mean BTEX concentrations all less than 100 ppm (77, 47, 1, and 1 ppm respectively). Radon concentrations in natural gas r were reported for a single FERC project in the northeastern US (mean 27.0 pCi l−1, range 20.4–40.8 pCi l−1) and were similar to previously reported radon data for northeastern US natural gas sampled from multiple pipelines (mean 28.5 pCi l−1, range 16.9–44.1 pCi l−1) (Anspaugh 2012).

Pipeline operators also reported liquid phase HAPs in condensate liquids and, for a small subset of pipelines, polychlorinated biphenyls (PCBs) were also reported as present (supplemental table S2). PCB contamination of some transmission pipelines is the result of historical usage of lubricating oils containing PCBs in compressor stations prior to the ban on their use in the US (Erickson and Kaley 2011).

While no regulatory limits exist for HAPs present in natural gas, table 2 provides ambient air regulatory limits for comparison of HAPs identified in this study. Notably, direct comparisons are not applicable as exposures to pure hydrocarbon streams are unlikely and releases would adhere to dispersion

5 https://infopost.bwpipelines.com/frameset.aspx?url=%2FPosting%2FGasCompositionPage.aspx&tspid=1.
and dilution dynamics. Nonetheless, for natural gas, reported HAP concentrations were higher than US EPA Reference Concentration limits but generally under other health-based limits with the exception of benzene. For condensate vapor and flash gas, reported HAP concentrations were one or two orders of magnitude higher than various health-based limits including occupational short-term exposure limits for BTEX compounds (table 2).

3.3. Factors associated with natural gas HAP concentrations

HAP concentrations were compared across EIA natural gas regions to test whether geography influences natural gas HAP composition. There was a significant effect of region for hexane (Kruskal–Wallis $\chi^2 = 11.2$, $p < 0.05$), benzene ($\chi^2 = 16.7$, $p < 0.01$), and toluene ($\chi^2 = 13.5$, $p < 0.01$) concentrations. However, only the difference between benzene concentrations in the Midwest versus the Northeast were significant by post-hoc testing (higher for the Midwest by the Dwass-Steel-Critchlow-Fligner test, $W = 3.976$, $p < 0.05$).

Subsidiaries of just three large parent midstream pipeline companies (labeled as Company 1, 2, and 3) accounted for 49% of all project applications. When comparing HAP concentrations, there was a significant effect of parent company with respect to each of the BTEX compounds by Kruskal Wallis test (benzene $\chi^2 = 11.9$, toluene $\chi^2 = 9.8$, ethylbenzene $\chi^2 = 12.6$, xylene $\chi^2 = 14.3$, all $p < 0.01$) but not for hexane, 2,2,4-trimethylpentane, or hydrogen sulfide (all $p > 0.05$). Nonparametric post-hoc comparisons using the Dwass-Steel-Critchlow-Fligner test indicated that each of the BTEX, but not hexane, concentrations reported for Company 1 subsidiary pipelines were significantly higher than concentrations reported for Company subsidiaries (benzene $W = 5.2$, toluene $W = 5.0$, ethylbenzene $W = 4.8$, xylene $W = 4.8$, all $p < 0.01$). Xylene concentrations reported for the Company 1 subsidiary pipelines were also significantly higher than for Company 2 subsidiaries ($W = 3.74$, $p < 0.5$). The differences between the Northwest and Southwest regions did not appear attributable to the effect of parent companies; project applications were not distributed differently across EIA regions for the three large parent companies (chi square test $\chi^2 = 8.45$, $p = 0.207$). These effects were likely driven almost entirely by data reported for one subsidiary pipeline of Company 3 (10 of 10 parent company observations) and one Company 1 subsidiary pipeline (9 of 10 parent company observations). Both pipelines transport natural gas between the Southwest and Northwest EIA regions.

3.4. Comparison of FERC project application data to a real-time data set

We evaluated the real-time natural gas HAP composition reported via informational postings for five pipelines that were also in the FERC application data (figure 4).

For all five pipelines, median HAP concentrations were highest for benzene and tended to be lower for ethylbenzene, but qualitatively similar for toluene and xylenes. Reported BTEX and hydrogen sulfide concentrations ranged substantially, by several orders of magnitude for all pipelines except for Pipeline C. Xylene concentrations were reported as higher for Pipeline A than any other HAP for the date range studied (up to 6324 ppm).
Table 1. HAP composition of transmission pipeline natural gas and other transmission sector gases. Pipeline natural gas, separator flash gas, and condensate tank vapor can be released during routine operation of natural gas transmission pipeline compressor stations. Values are reported in ppm with the exception of radon, which is reported in pCi L\(^{-1}\). Data were obtained from all approved FERC applications for new or expanded natural gas transmission projects and new or expanded LNG projects, 2017–2020. Radon data were taken from an industry filing included with one FERC project application. Projects that did not report any data for a given HAP were not included in the statistical calculations. The 2,2,4-TMP; 2,2,4-trimethylpentane. H2S: hydrogen sulfide.

| HAP           | Pipeline natural gas | Separator flash gas | Condensate tank vapor | LNG associated natural gas |
|---------------|----------------------|---------------------|-----------------------|----------------------------|
|               | n | Mean (SD) | Range               | n | Mean (SD) | Range               | n | Mean (SD) | Range               | n | Mean (SD) | Range               |
| Hexane        | 58 | 114 (132) | 0–450               | 17 | 4597 (2918) | 0.0322–8569         | 16 | 18 956 (13 864) | 1.14 × 10\(^{-6}\)–46 812.9 | 15 | 189 (301) | 0–1219             |
| Benzene       | 43 | 37 (66)   | 0–299               | 17 | 1106 (1005) | 0.6897–41 008       | 16 | 7050 (6025) | 0.013 422–14 7996  | 13 | 77 (163) | 0–600              |
| Toluene       | 40 | 19 (34)   | 0–160               | 17 | 1508 (2635) | 0.4260–11 340       | 16 | 7155 (7767) | 0.001 724–23 270  | 10 | 47 (92) | 0–300              |
| Ethylbenzene  | 35 | 3 (5)     | 0–20                | 16 | 96 (66)      | 9–187                | 13 | 668 (1661) | 0.21–6150          | 7  | 1 (4)   | 0–10               |
| Xylenes       | 37 | 11 (15)   | 0–50                | 16 | 856 (925)    | 75–4078             | 13 | 4226 (8090) | 0.2–28 840         | 5  | 1 (2)   | 0–5                |
| 2,2,4-TMP     | 23 | 4 (5)     | 0–16                | 12 | 79 (217)     | 0–766               | 12 | 28 (38)    | 0–80.3             | 3  | 1 (2)   | 0–3.9              |
| H2S           | 13 | 1 (1)     | 0–4                 | 4  | 5134 (3422)  | 0–6868             | 5  | 3320 (5449) | 0–12 928           | 8  | 3 (3)   | 0–8                |
| Radon (pCi L\(^{-1}\)) | 12 | 27.0 (7.6) | 20.4–41.8           |                   |                 |                   |                 |                 |                   |                 |
Table 2. Health-based ambient exposure limits for HAPs identified in the natural gas transmission sector. The ACGIH OSHA and Cal/OSHA standards are used in occupational settings, while OEHHA RELs are used in community health assessments. The US EPA RfC (reference concentration) is an estimate of a continuous inhalation exposure concentration to people (including sensitive subgroups) that is likely to be without risk of deleterious effects during a lifetime. STEL = short term exposure limit typically expressed as a 15 min time-weighted average concentration; TWA = time-weighted average typically 8 or 10 h averaging times; OEHHA REL = recommended exposure level, with exposure averaging time for acute RELs = 1 h and chronic RELs that are designed to address continuous exposures for up to a lifetime. Plotting the data by EIA natural gas region did not reveal any apparent trends other than that LNG projects were almost all planned for the Southwest region (figure 3).

| Compound                     | Occupational health benchmarks | Recommended limits |
|------------------------------|--------------------------------|--------------------|
|                              | OSHA (ppm) | Cal/OSHA (ppm) | NIOSH (ppm) | ACGIH (ppm) | USEPA RfC (mg m$^{-3}$) | OEHHA REL (µg m$^{-3}$) |
|                              | STEL | TWA | STEL | TWA | STEL | TWA | STEL | TWA | STEL | TWA | STEL | TWA | Acute | Chronic |
| Benzene                      | 5    | 1   | 5    | 1   | 1    | 0.1  | 2.5  | 0.5  | 0.03 | 27   | 3    |      |         |
| Toluene                      | 300  | 200 | 150  | 10  | 150  | 100  | 20   | 5    | 5000 | 420  |      |         |
| Ethyl-benzene                | —    | —   | 100  | 5   | 125  | —    | —    | 20   | 1    | —    | 2000 |      |         |
| Xylene (o-, m-, p-isomers)   | —    | —   | 100  | 150 | 150  | 100  | 150  | 100  | 0.1  | 22000 | 700  |      |         |
| (1330-20-7)                  |      |     |      |     |      |      |      |      |      |       |      |      |         |
| n-hexane (110-54-3)          | —    | 500 | —    | 50  | —    | 50   | —    | 50   | 0.7  | —    | 7000 |      |         |
| 2,2,4-trimethylpentane       | —    | —   | —    | —   | —    | —    | 300  | —    | —    | —    | —    | —    |         |
| Hydrogen sulfide             | 20   | —   | 15   | 10  | —    | —    | 5    | 1    | 0.002 | 42  | 10   |      |         |
| Radon (pCl$^{-1}$)           | —    | 100 | —    | —   | —    | —    | —    | —    | 4    | —    | —    | —    |         |

Figure 3. HAP concentrations for transmission pipeline natural gas and other transmission sector gasses by geographical region. Data were obtained from all approved FERC applications for new or expanded natural gas transmission projects and new or expanded LNG projects, 2017–2020. Projects were further categorized geographically based upon the pipeline construction project’s location within a given natural gas pipeline region as defined by the US EIA. Dashes represent mean concentrations. Zero values were not plotted given the logarithmic y axis, but were used to calculate mean concentrations. The 2,2,4-TMP: 2,2,4-trimethylpentane. H2S: hydrogen sulfide.

Comparing HAP concentrations between the FERC application data and the real-time data, there was no consistent relationship across the five pipelines. Pipeline A did not report any BTEX or hydrogen sulfide data in their FERC applications, although those HAPs were reported for its gas supplies. Benzene, toluene, and xylene concentrations for Pipeline B and Pipeline C application data were above the interquartile range for the real-time measurements, while their applications did not report the presence of ethylbenzene and hydrogen sulfide that were reported in their real-time measurements. Pipeline D application values were below the interquartile range for toluene and above...
Figure 4. Comparison of natural gas HAP concentrations reported by pipeline operators in FERC transmission pipeline expansion project applications (2017–2020) and concentrations reported for five transmission pipelines delivering gas through a pipeline interconnection point with Pipeline B (1 December 2020–1 July 2021); red filled circles and blue filled circles, respectively. Upper whisker equals 1.5 × IQR, lower whisker equals last value before 0 due to log scale. H2S: hydrogen sulfide.

Table 3. Reported real-time HAP composition of transmission pipeline natural gas from five operating pipelines (upper panel) and one nearby natural gas storage facility (lower panel), based upon measurements provided by one of the pipeline operators. Pipeline data consist of measurements taken at 5 min intervals from interconnection points between the five transmission pipelines and a single receiving pipeline. Reported data were collected from 1 December 2020 through 1 July 2021. All values are in ppm unless otherwise specified. Descriptive statistics were calculated by bootstrap analysis due to non-normal distributions for some pollutants reported in some pipelines. H2S: hydrogen sulfide.

| Pipeline-associated natural gas                  | HAP | n   | Mean (ppm) | SD    | 95% CI     |
|------------------------------------------------|-----|------|------------|-------|------------|
| Benzene                                        | 208 | 233 | 5.9        | 6.0   | 0.0, 17.6  |
| Toluene                                        | 208 | 233 | 3.7        | 3.6   | 0.0, 10.8  |
| Ethylbenzene                                   | 208 | 233 | 0.2        | 1.2   | 0.0, 2.5   |
| Xylenes                                        | 208 | 233 | 8.5        | 103.6 | 0.0, 211.6 |
| H2S                                            | 187 | 562 | 1.0        | 0.7   | 0.0, 2.4   |
| Mercury (ng m⁻³)                               | 55  | 309 | 3.4        | 22.3  | 0.0, 47.0  |

| Storage-associated natural gas                  | HAP | n   | Mean (ppm) | SD    | 95% CI     |
|------------------------------------------------|-----|------|------------|-------|------------|
| Benzene                                        | 53  | 940 | 6.1        | 2.3   | 1.6, 10.6  |
| Toluene                                        | 53  | 940 | 5.6        | 2.4   | 0.9, 10.4  |
| Ethylbenzene                                   | 53  | 940 | 0.3        | 0.3   | 0.1, 1.0   |
| Xylenes                                        | 53  | 940 | 1.9        | 1.5   | 0.7, 6.8   |
| H2S                                            | 997 | 1   | 0.5        | 0.3   | 0.0, 1.0   |
| Mercury (ng m⁻³)                               | 53  | 926 | 9.3        | 18.0  | 0.0, 44.5  |

The interquartile range for hydrogen sulfide, while Pipeline E application values were variously above or below the interquartile range for the reported real-time measurements. Additionally, mercury was not reported in any FERC applications but was reported as detected in 14% of real-time pipeline measurements (table 3). The informational postings source also reported the same 5 min BTEX, hydrogen sulfide, and mercury values for a nearby depleted gas reservoir underground natural gas storage facility. Bootstrapped BTEX, hydrogen sulfide, and mercury means for the reported storage-associated natural gas concentrations were within one standard deviation.
of the corresponding pipeline bootstrapped means (table 3). However, mercury was reported as detected in 96% of storage-associated natural gas measurements relative to the 14% reported detection rate for pipeline natural gas.

3.5. Predictors of hazardous pollutant disclosures
We sought to identify factors associated with the reporting of hazardous pollutants in FERC project applications using logistic regression analyses. The regression model included geographic site of project construction (EIA region), year of project filing, whether the project added miles of pipeline, and whether the project added compression via a new or upgraded compressor station. Only the addition of compression was a significant predictor of whether any natural gas HAP composition data were reported (unadjusted odds ratio 14.54, 95% CI 4.86–43.46), where projects that added new compression capacity were more likely to report HAP composition data.

4. Discussion
Natural gas that has been produced but not yet fully processed for delivery to the interstate transmission pipeline system is known to contain HAPs (Warneke et al 2014, DiGiulio and Jackson 2016, Faramawy et al 2016). Prior to this study, there have been no peer-reviewed investigations of natural gas composition in the US interstate transmission pipeline system. Our evaluation of publicly available industry-reported data indicates that natural gas in the transmission sector (including interstate pipelines, LNG facilities, and underground natural gas storage facilities) appears to contain detectable concentrations of HAPs. By determining the concentrations of HAPs associated with transmission pipeline natural gas and associated emissions sources, this study provides a rational foundation for health-based risk assessments of emissions events from transmission infrastructure including fugitive emissions, venting or blowdowns, and loss of containment events.

4.1. Assessment of transmission pipeline natural gas emissions
The data reported here represent the best available estimates for HAP concentrations in transmission pipeline natural gas to date. These data can be utilized to estimate air quality impacts and health risks that could result from exposure to natural gas when emitted to the atmosphere. For example, HAP concentrations from this study could be combined with observed methane concentrations in ambient air during accidental or intentional natural gas releases, or to determine the concentration of natural gas in ambient air that could produce an exposure in excess of health-based limits or benchmarks. Using the latter strategy in a rough calculation with the 90th percentile for natural gas benzene concentrations from this study (100 ppm), the OEHHA REL for benzene (~0.001 ppm) (California Office of Environmental Health Hazard Assessment 2014) could be exceeded for an 8 h exposure to natural gas at concentrations of 10 ppm (not accounting for benzene from other sources). Methane concentrations from transmission sector loss of containment events can substantially exceed 10 ppm; for example, methane concentrations from the 2015 Aliso Canyon natural gas storage well blowout were measured up to 630 ppm (Conley et al 2016).

The routine operation of transmission natural gas facilities also entails the release of natural gas through fugitive emissions and blowdowns. One study estimated that 54% of compressor station methane emissions originated from non-combustion sources such as pneumatic controllers, compressor seal leaks, other fugitive emissions, and blowdowns (Johnson et al 2015). Numerous studies have measured either methane plumes attributable to site-wide emissions including combustion sources (Jakober et al 2015, Lavoie et al 2015, Yacovitch et al 2015, Payne et al 2017, Casworth et al 2021) or have measured methane flux rates for unburned natural gas emitted by transmission facilities (Subramanian et al 2015). One study (Thorpe et al 2020) reported methane plume concentrations for unburned gas emitted as fugitive emissions from natural gas storage facilities, with a maximum concentration for the plumes of 4000 ppm. Applying this study’s median benzene concentration of 6.1 ppm for storage-associated natural gas would yield an estimate of up to 25 parts per billion benzene in the plume, assuming a 95% methane concentration in the gas (4000 ppm methane in air × 1/(0.95 natural gas/methane) × 6.1 ppm benzene in natural gas = ppm benzene in air). This example demonstrates an approach for a first pass approximation of air quality impacts due to HAP emissions from unburned natural gas.

In addition to potential exposures from transmission sector emissions, one recent study identified hexane and BTEX in natural gas delivered to homes through the distribution system in the greater Boston area (Michanowicz et al 2022). Since natural gas leaks from the Boston distribution system (Phillips et al 2013, Sargent et al 2021), and natural gas appliances in the home can leak unburned natural gas (Lebel et al 2020, 2022), it appears possible that the transmission sector delivers HAPs into the distribution system where they can be released into the indoor and outdoor environment, in close proximity to substantial numbers of people. The identification of hexane and BTEX in natural gas from the production sector, distribution sector, and now the identification of hexane and BTEX in the transmission sector suggests that HAPs may travel throughout the entire natural gas supply chain and result in HAP exposures at various points along that supply chain.
4.2. Natural gas transmission pipelines contain a diverse group of toxic pollutants

Although radon, the leading cause of lung cancer in non-smokers (Cheng et al 2021), is a known constituent of natural gas (van Netten et al 1998, Kitto et al 2014, Nowak et al 2020), this study identified additional radon data that, to the best of our knowledge, have not yet been analyzed and published outside of the FERC document library. Mercury is similarly associated with natural gas formations (Yan et al 2017) and known to contaminate natural gas (Chalkidis et al 2020), but we are not aware of any previous studies that quantified mercury in transmission pipeline natural gas specifically. These data, along with those of other heavy metals such as lead, arsenic, and cadmium in natural gas (Cachia et al 2018), warrant additional investigation to clarify the extent of heavy metal contamination in the natural gas sector, especially considering the present study did not include any mercury data from the western US geologic mercury belt where geologic mercury formations in proximity to oil and gas producing regions are more concentrated (Yan et al 2017). PCBs were reported in a limited number of transmission pipelines due to the historical use of PCB-containing lubricants in transmission pipeline infrastructure (Erickson and Kaley 2011). While PCBs may be relatively contained in the liquid phase, there have been incidents of PCB releases from natural gas transmission infrastructure to the environment (Anon 1991, 1994).

4.3. Implications for federal transmission project reviews

The FERC data presented here appear to be disclosed primarily to satisfy environmental reporting requirements. Namely, the FERC environmental reporting guidance recommends, but does not require, natural gas HAP composition data for some project applications. Our analysis indicates that the only predictor of whether a project would disclose its natural gas HAP composition was if the project included new or expanded compressor station capacity, likely reflecting the greater scrutiny of air pollutant emissions for these types of projects from both FERC and state regulators. For the 51% of projects that did not report any natural gas HAP data, it is unclear whether or not the absence of data indicates that the natural gas for those projects does not contain HAPs. For example, one pipeline did not report any HAPs in natural gas as part of their FERC applications despite the reported BTEX and hydrogen sulfide from the real-time informational postings data. Air quality and health-based evaluations of transmission infrastructure emissions will remain constrained by these missing data until FERC policies are updated to require, not simply recommend, consistent disclosure of natural gas HAP composition data and/or additional real-time reporting of natural gas HAP concentrations.

4.4. Study validity and limitations

While this study provides a unique hazard identification analysis of potential HAP sources in the natural gas transmission sector, it remains possible that any given facility may employ one or more emission controls to mitigate release of the sources characterized here. For example, although oil and gas storage tanks can utilize emissions control devices such as vapor recovery units, those were not noted during the initial data collection. We subsequently reviewed any available approved air permits for projects in the study, and if unavailable also reviewed air permit applications and equipment descriptions from FERC application materials (supplemental information section 4). Although there were no identifiable emissions control devices for any condensate tank or separator flashing emissions on this additional review, it remains possible that emissions controls that might mitigate emission of the HAP sources described here.

The data presented in this study were taken from natural gas industry sources, but these may not be representative of actual HAP concentrations across facilities and over time. Project application source table captions or footnotes, when present, mostly referred to HAP concentrations as ‘representative’ or ‘average’ but were typically not described in further detail. Although natural gas concentrations were usually reported as resulting from gas chromatography analysis when the source data were referenced at all, the flash and condensate vapor data relied on software estimates such as the US EPA Tanks program that may not provide highly accurate estimates of condensate composition.

Finally, the publicly available data analyzed in this study represent natural gas composition disclosures for 44.7% of the US onshore natural gas transmission system by pipeline mileage. While this study addresses a significant proportion of the US transmission system, additional data from the remainder of the transmission system are needed.

4.5. Conclusions

This is the first peer-reviewed study of HAP concentrations in natural gas flowing through interstate transmission pipelines and associated infrastructure in the US. We found that HAPs are ubiquitous throughout the transmission system including pipelines, LNG facilities, and storage facilities. Moreover, associated emissions sources such as flash gas and condensate vapor were reported to contain extremely high concentrations of HAPs. This study strongly suggests that routine natural gas releases and loss of containment events in the natural gas transmission sector are not only an issue pertinent to flammability, explosions and climate forcing from methane, but also a concern for air quality degradation and potential human exposure to elevated concentrations of HAPs, including toxic and/or carcinogenic volatile...
organic compounds, hydrogen sulfide, radon, and mercury.

Data availability statement
The data that support the findings of this study are available upon request from the authors.

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