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Natural Gas Pipeline Replacement Programs Reduce Methane Leaks and Improve Consumer Safety

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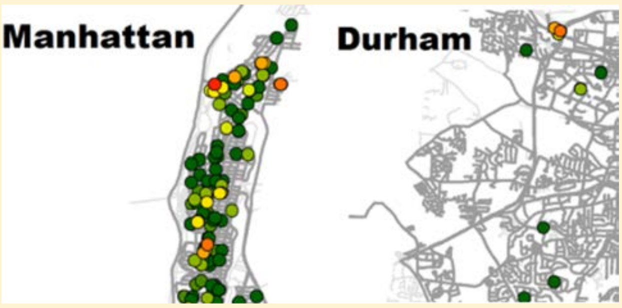
Supporting Information



ABSTRACT: From production through distribution, oil and gas infrastructure provides the largest source of anthropogenic methane in the United States and the second largest globally. Using a Picarro G2132i Cavity Ring-Down spectrometer, we mapped natural gas leaks across the streets of three United States cities—Durham, NC, Cincinnati, OH, and Manhattan, NY—at different stages of pipeline replacement of cast iron and other older materials. We identified 132, 351, and 1050 leaks in Durham, Cincinnati, and Manhattan, respectively, across 595, 750, and 247 road miles driven. Leak densities were an order of magnitude lower for Durham and Cincinnati (0.22 and 0.47 leaks/mi, respectively) than for Manhattan (4.25 leaks/mi) and two previously mapped cities, Boston (4.28 leaks/mi) and Washington, DC (3.93 leaks/mi). Cities with successful pipeline replacement programs have 90% fewer leaks per mile than cities without such programs. Similar programs around the world should provide additional environmental, economic, and consumer safety benefits.

INTRODUCTION

Shale gas and other unconventional natural gas production can help reduce United States carbon dioxide (CO_2) emissions if methane emissions from natural gas infrastructure are minimized.[1] Emissions during the production, processing, storage, transmission, and distribution of oil and gas were the second largest anthropogenic source of methane to the atmosphere globally in 2013.[2] Such emissions are important because methane's global warming potential (GWP) is 87 times greater than that of CO_2 over 20 years and 36 times larger over 100 years.[3]

Reducing natural gas emissions during extraction, processing, and pipeline delivery has additional environmental, economic, and human health benefits.[4−11] Methane, ethane, and other hydrocarbons react with nitrogen oxides (NO_x) and can lead to tropospheric ozone pollution.[4] The average economic loss of natural gas leaked or emitted from pipelines in the United States in 2013 was estimated to be $2.1 billion.[7]

Natural gas pipeline safety in the United States has improved over recent decades,[6] but rare accidents still occur associated with aging infrastructure and from excavations and human error. In 2014, there were 65 reported gas distribution pipeline incidents in the United States, with 18 fatalities, 93 injuries, and more than $73 million in property damage, surpassing the five year average (2010−2014) in each category.[6] Such risks and impacts to the environment, economy, and human health led the U.S. Department of Transportation's (USDOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) to issue a Call to Action in 2011 to "accelerate the repair, rehabilitation, and replacement of the highest-risk pipeline infrastructure."[9] Pipeline age and material (specifically wrought and cast iron and bare steel pipelines) are indicators of higher risk pipelines frequently targeted for replacement.

A number of studies have shown that age and material type of distribution pipelines correlates with leak frequency.[10−14]

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Phillips et al.[10] found 3356 methane leaks over 785 road miles surveyed in Boston, MA, and showed a strong relationship between the number of leaks per neighborhood and the number of miles of cast iron mains per neighborhood ($R^2 = 0.79$). Jackson et al.[11] found 5893 leaks over 1500 road miles in Washington, DC, that contained about 406 miles of cast iron mains. Aging natural gas infrastructure, particularly cast iron and unprotected steel pipelines, presents an opportunity for economic and environmental benefits if leaks and emissions can be identified easily and pipelines repaired or replaced economically.

For this study, we mapped natural gas leaks across the streets of three United States cities—Durham, NC, Cincinnati, OH, and Manhattan, NY—with different replacement plans and at different stages of completion (completed replacement, accelerated replacement, and general replacement, respectively). We compare these leak densities with previously mapped systems in Boston[10] and Washington, DC,[11] to examine the efficacy of accelerated pipeline repair and replacement programs.

METHODS

Between February and July 2014, we surveyed three cities (Durham, NC, Cincinnati, OH, and Manhattan, NY) for methane concentration [CH_4] on city streets using a mobile Picarro G2132i Cavity Ring-Down spectrometer (CRDS)/surveyor for Natural Gas Module 2 − Investigator unit (Picarro, Inc., Santa Clara, CA). The methods employed follow those described in Phillips et al.[10] and Jackson et al.[11] and are described briefly here. An individual leak or source was defined conservatively as a spatially contiguous set of [CH_4] observations greater than 2.5 ppm (i.e., >20% above background [CH_4] of 1.8−2.0 ppm of CH_4) with a distance threshold radius greater than 5 m from any other elevated [CH_4] observation.[10,11] To detect leaks, the methane analyzer was installed in the back of a vehicle, with a sample line running from the front bumper of the vehicle to the instrument's sample inlet. Atmospheric air was sampled about 0.3 m above the road surface and continuously recorded every approximately 1 s. Inlet ports were covered with a gas-permeable membrane to prevent water from entering the system. A GPS and two-dimensional sonic anemometer (WindSonic: Ultrasonic Wind Sensor; Gill Instruments, Ltd., Hampshire, U.K.) were installed on the roof of the vehicle to give real time location (latitude/longitude) and wind speed and direction data (Tables S1−S3). The wind data were supplemented with additional wind and weather data from nearby National Oceanic and Atmospheric Administration (NOAA) weather stations supplying Quality Controlled Local Climatological Data (QCLCD), also available through NOAA's National Climatic Data Center (NCDC) (Tables S1−S3). The time stamp of the [CH_4] observation was corrected for the short time lag between sampling at the bumper inlet and instrument measurement attributable to the length of the inlet tube. Some New York observations had large GPS positioning errors attributable to interference of the GPS signals by tall buildings. Any points that deviated by 10 m or more from the road observation were removed from our analysis. Leaks were expressed per city road mile to compare leak densities. Although the EPA[2] estimates that most methane losses are from mains rather than service lines (430 Gg compared to 190 Gg, respectively), we also compared observed leaks to the number of service lines per mile of main to examine any effects of higher service line densities in dense urban areas. The number of service lines per mile of main ranged by a factor of two across the five cities: 49, 72, 86, 61, and 103 service lines per mile for Durham, Cincinnati, Manhattan, Boston, and Washington, DC, respectively.[15] We did not have access to data for underground regulator stations, but there are only 560 across all of New York City and only about 100 in Manhattan;[16] as such, they are unlikely to affect our results substantively.

To confirm the accuracy and consistency of the concentrations measurements, a 5 ppm [CH_4] standard was measured on the instrument periodically throughout the survey, with concentration values always within 0.3 ppm of CH_4. Additionally, we measured independent standard sample bags [(1) 5 ppm, −38.0‰, (2) 20 ppm, −36.8‰, (3) zero air (Airgas, Inc., Durham, NC)] periodically to confirm concentration measurements. Values were always within 0.2, 0.7, and 0.1 ppm of the known values for the 5 ppm, 20 ppm, and zero gas standards, respectively.

We used the Picarro G2132i Investigator to capture $\delta^{13}CH_4$ of a subset of street sources to differentiate between biogenic and thermogenic methane sources. Signatures of $\delta^{13}CH_4 > -40‰$ (reference to Vienna Pee Dee Belemnite standard) generally suggest a thermogenic source for methane, whereas $\delta^{13}CH_4$ values $< -60‰$ suggest a biogenically derived source.[17,18] During the original surveys, isotopic capture measurements were made at seven to eight sites in each city, with three and four repeated captures in Cincinnati and Durham, respectively, to confirm repeatability (1.6 ± 0.8‰; all values mean ± s.d. unless otherwise noted). We took additional isotopic captures in July for both Durham (eight captures) and Manhattan (six captures) several months after the original surveys to assess potential changes in isotopic signature. For Durham, the average isotopic signature was within 2.5‰ of the original survey (−41.3 ± 2.2‰ for the March survey and −38.8 ± 1.7‰ in July) and similar to a value of −41.6‰ for a direct pipeline sample measured on a Picarro G2132i CRDS at the Duke Environmental Stable Isotope Laboratory (DEVIL). Captures made in Manhattan also showed less than 3.2‰ difference on average (−24.3 ± 2.6‰ for the May survey and −27.5 ± 4.5‰ in July). Both sets of measurements confirmed the sustained presence of the leaks and their thermogenic nature. In addition, evacuated cylinders or sample bags were collected using a hand pump at a subset of the Durham and Manhattan sites visited in July; these samples were then analyzed for [CH_4] and $\delta^{13}CH_4$ on the Picarro G2132i CRDS at the DEVIL within 2 days of sampling to compare field isotopic measurements with laboratory measurements. Laboratory analyses of bag and cylinder samples were 2.7 ± 1.1‰ (mean ± s.e.; $n = 6$) lighter than car field measurements, suggesting a slight bias in the driving instrument (likely attributable to ethane interference) but not large enough to alter determinations of thermogenic versus biogenic sources.

Standard sample bags filled with either 100 ppm, −36.8‰ (Airgas, Inc., Durham, NC) or 2500 ppm, −66.5‰ (Airgas, Inc., Durham, NC) $\delta^{13}CH_4$ standard gases were used to release small puffs of gas standard near the bumper inlet to simulate a plume. On average, the isotope capture was −1.0‰ heavier than the known delta for the 100 ppm standard and −1.5‰ heavier than the known delta for the 2500 ppm standard (−35.84 ± 0.86‰ ($n = 5$) and −65.03± 0.78‰ ($n = 4$), respectively).

In June and July of 2015, we carried out two follow-up field campaigns to gather additional data. To confirm that most of

Table 1. Street Leak Comparison of Five Major United States Cities[a]

city	road miles driven	total # of leaks	leaks/mile	leaks >5ppm	leaks >10ppm	leaks >25ppm	mean (ppm)	median (ppm)	max (ppm)	% rep. can. (mains)	% rep. can. (service lines)	service lines/mi of main (#/mi)	leaks/mi normalized by service lines/mile of main
Washington, DC	1,500	5,893	3.93	1122	334	67	4.6	3.1	88.6	43%	25%	103	0.0381
Boston, MA	785	3,356	4.28	435	97	1	3.7	2.9	28.6	37%	23%	61	0.0706
Manhattan, NY	247	1,050	4.25	186	53	11	4.5	3.1	60.0	52%	23%	86	0.0493
Cincinnati, OH	750	351	0.47	66	19	5	4.7	3.1	54.3	2%	12%	72	0.0065
Durham, NC	595	132	0.22	24	10	4	4.7	3.0	33.1	0%	0%	49	0.0045
Durham, NC, 2015	145	46	0.33	5	4	0	3.8	2.9	12.7	0%	0%	49	0.0045

[a] Percent replacement candidate for mains and service lines calculated from PHMSA data[15] for the year of each study (2014 for Manhattan, Durham, and Cincinnati; 2013 for Washington, DC;[11] 2011 for Boston[10]). The second Durham entry reflects the results of 145 miles of the city re-driven at night in 2015.

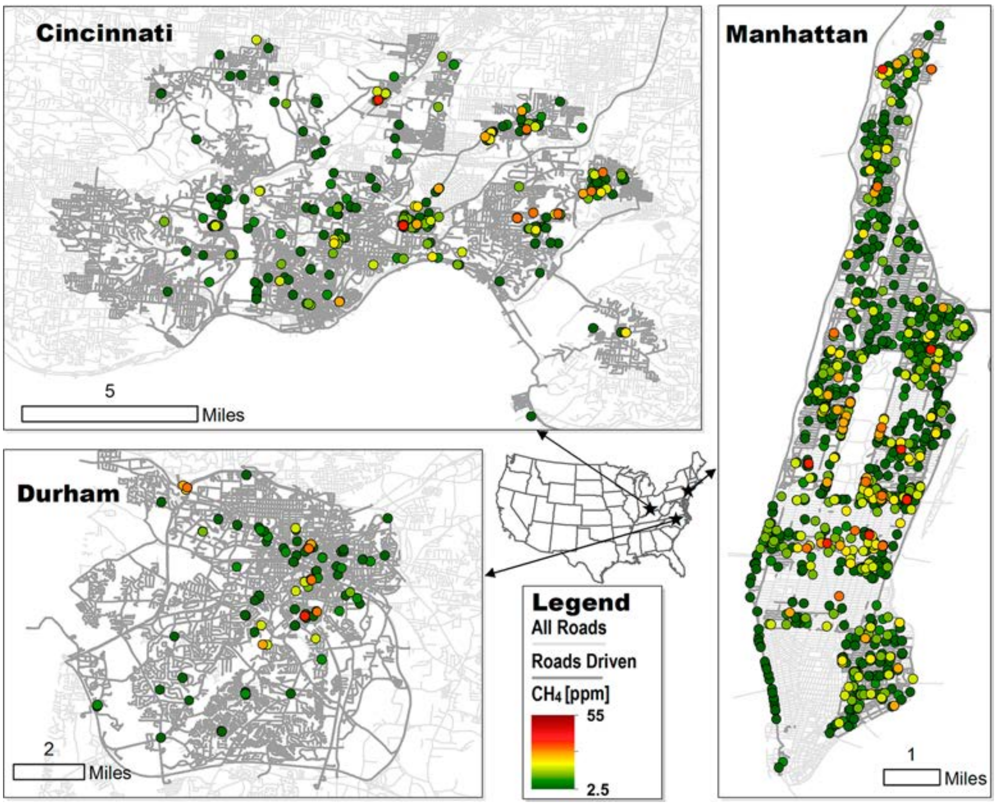

Figure 1. Maps of methane leaks surveyed in Cincinnati, OH (top left), Durham, NC (bottom left), and Manhattan, NY (right). Roads driven are outlined in darker gray, with leak locations marked by colored circles for CH_4 concentration. Note that the map scales vary for the three cities. See Table 1 for information on road miles driven, total leaks, and leaks per mile.

the observed leaks came from underground infrastructure instead of other city infrastructure, including buildings, aboveground meters, and other sources, we identified the source of all leaks identified in four sections of Manhattan (Figure S1, Table S4). For each of the 42 leaks identified, we used a flame ionization detector (Dafarol A-600; Dafarol Associates, Hopedale, MA) and a Bascom−Turner combustible gas analyzer to locate and attribute the source of each leak detectable from the survey. The second field campaign was to eliminate any possibility that the leak densities observed in Durham were associated with higher wind speeds or any other weather conditions. We re-drove 145 road miles of Durham (24% of the original survey) in five areas from 10pm to 8am (July 27−29, 2015) (Figure S2). During this nighttime window, the air was still (Table S5), which would lead to a maximum number of leak detections. Leak locations and densities were then compared to results from the 2014 survey.

To provide context for the city observations, we analyzed pipeline material data collected by the USDOT's PHMSA annually from gas distribution operators (www.phmsa.dot.gov − Distribution, Transmission & Gathering, LNG, and Liquid Annual Data) for the years 2000 to 2014.[15] We analyzed pipeline materials data from 2013 for all United States states from 2000 to 2014 for distribution operators that service Manhattan (Operator ID: 2704), Cincinnati (ID: 2364), and Durham (ID: 15938)[19−21] and from 2013 for Washington, DC

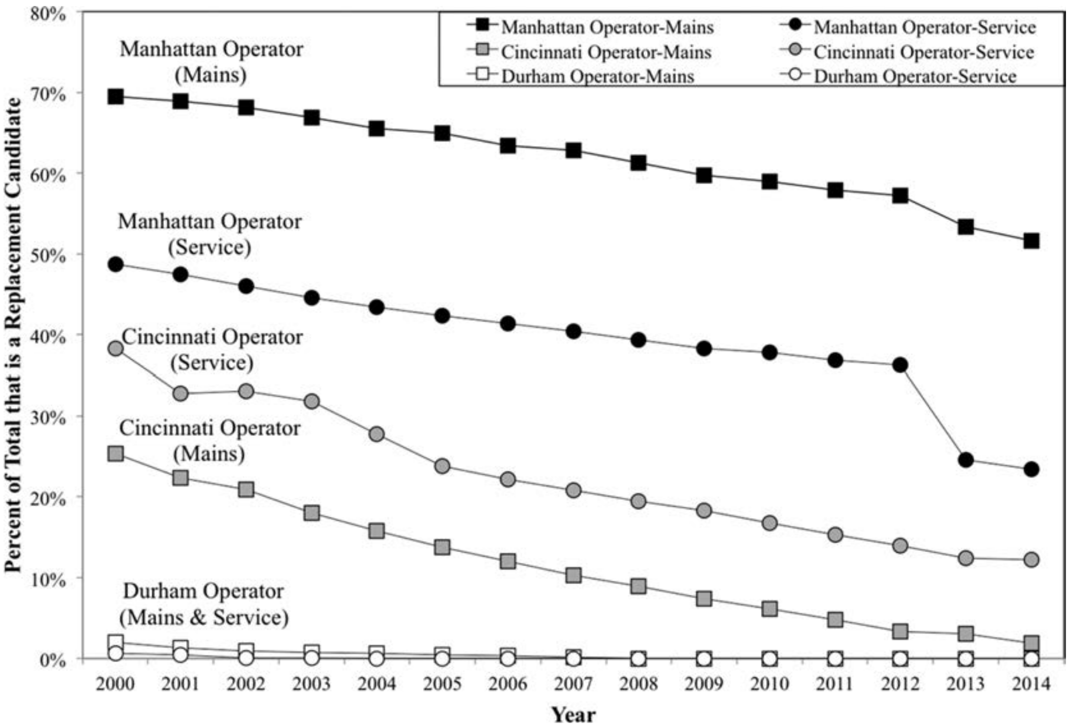

Figure 2. Percent of total pipelines that are replacement candidates in different areas. The figure shows the percentage of the total miles of main or service lines from 2000 through 2014 that are replacement candidates (unprotected bare or coated steel, cast/wrought iron, ductile iron, copper, and other) for Manhattan, NY, Cincinnati, OH, and Durham, NC, as reported by company.[15]

(ID: 22182) and 2011 for Boston (ID: 2652),[21] the years of sampling for each city (Table 1). In addition to reporting total miles of mains and number of service lines, gas distribution companies report miles of main or number of service lines by material type (unprotected bare steel, unprotected coated steal, cathodically-protected bare steel, cathodically-protected coated steel, plastic, cast/wrought iron, ductile iron, copper, and other). Materials that are considered "replacement candidates" are defined as unprotected bare or coated steel, cast/wrought iron, ductile iron, copper, and other. We calculated the percent replacement candidate as the miles of mains that are replacement candidates per total miles of mains or the number of service lines that are replacement candidates per total number of service lines. Percent replacement candidate is calculated with data collected for the year of each study: 2014 for Manhattan, Cincinnati, and Durham; 2013 for Washington, DC; 2011 for Boston. PHMSA data are the only publicly available data source for such analyses but should be interpreted with caution. Changes in the amount of pipeline materials for a given operator can arise not just through replacement programs but through reclassification (e.g., when an operator realizes that a protective steel coating is no longer functioning) or when companies merge or sell assets.

■ RESULTS AND DISCUSSION

We observed 132, 351, and 1050 street leaks for Durham, Cincinnati, and Manhattan, respectively, across the 595, 750, and 247 road miles surveyed in each city (Figure 1). Leak densities were an order of magnitude lower for Durham and Cincinnati (0.22 and 0.47 leaks/mi, respectively) than for Manhattan (4.25 leaks/mi) and for those observed previously in Boston (4.28 leaks/mi) and Washington, DC (3.93 leaks/mi) (Table 1). Manhattan also had 3 to 5 times more high-concentration leaks (>10 ppm) than Cincinnati or Durham despite having less than half the road miles surveyed. Manhattan had 53 leaks with concentrations greater than 10 ppm of CH$_4$ (Table 1). Cincinnati and Durham had only 19 and 10 leaks greater than 10 ppm of CH$_4$, respectively. Manhattan also had the highest CH$_4$ concentration observed across the three cities, 60 ppm, compared to maximum observed values of 54 and 33 ppm in Cincinnati and Durham, respectively (Table 1). When leak densities were normalized by the number of service lines per mile of main, Durham and Cincinnati still had 5- to 10-fold lower values than Manhattan, Boston, or Washington, DC (0.0045, 0.0065, 0.0493, 0.0706, and 0.0301 leaks per service line, respectively).

The resurvey of Durham roads in 2015 during the still, nighttime conditions (Figure S2, Table S5) found a higher leak density than in 2014 but confirmed that Durham had the lowest leak densities of any city in the survey. Across 145 road miles driven (24% of the original dataset), we found 46 leaks at concentrations of 2.5 to 13 ppm of CH$_4$, with only 5 leaks greater than 5 ppm. The observed leak density was 0.33 leaks per mile, 50% higher than in the daytime conditions of 2014 when the leak density for Durham was estimated to be 0.22 leaks/mi (for both the full city survey and the subset of roads re-driven in 2015). Manhattan's leak density of 4.25 leaks/mi was still 13 times higher than the revised nighttime survey of Durham.

Real-time isotopic measurements showed that the observed CH$_4$ came from thermogenic rather than biogenic sources. Durham leaks had the lightest δ^{13}CH$_4$ signature of the three cities surveyed (−41.3 ± 2.2‰) but were still considerably heavier than biogenic sources. Cincinnati and Manhattan CH$_4$ leak signatures were even heavier (−36.1 ± 2.6‰ and −24.3 ± 2.6‰, respectively). In comparison, biogenic isotope values ranged from −53.1 to −64.5‰ for eight landfill, wetland, and sewage treatment sites in Boston, MA, sampled previously.[10]

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A detailed sampling of leaks in four randomized regions of Manhattan showed that emission sources from under streets rather than from buildings or other aboveground sources were responsible for the leaks observed. Of the 42 leaks surveyed to isolate the source (Figure S1), 41 (98%) clearly originated from street infrastructure, including manhole covers, valve boxes, and other locations (Table S4). The source of only one leak was ambiguous, as both a building fan and a street repair showed elevated concentrations of methane.

Accelerated pipeline replacement programs help explain the order-of-magnitude lower densities of leaks observed in Durham and Cincinnati compared to Manhattan (Table 1; Figure 1) and to Boston, MA,[10] and Washington, DC.[11] The percentage of replacement candidate mains and service lines was strongly related to leak densities for the five cities overall (r^2 = 0.95 and 0.85, respectively). Durham, which had the lowest density of leaks observed here (0.22 leaks/mile; Table 1), had replaced all of its cast iron and unprotected steel natural gas pipelines by 2008;[22] all mains in its distribution system are now either plastic (60%) or cathodically treated coated steel (40%). Similarly, an accelerated pipeline replacement program in Cincinnati,[23] a city with only 0.47 leaks/mi (Table 1), is almost complete, with only 3% of cast/wrought iron mains remaining across its network; the remaining 97% of its mains are comprised of plastic (50%) and cathodically protected coated steel (47%). Replacement candidate pipelines have steadily decreased in miles remaining for all three cities surveyed here, but they are much lower in Durham and Cincinnati than in Manhattan, Boston, or Washington, DC (Table 1; Figure 2). Continued replacements should help reduce CH_4 emissions from urban infrastructure.[24] A recent analysis in Boston, for instance, showed that the average regional CH_4 flux was 18.5 ± 3.7 g CH_4 m^{-2} y^{-1}, with 60–100% attributable to natural gas losses; the average fractional loss to the atmosphere from all downstream components of the natural gas system was 2.7 ± 0.6%, more than double the 1.1% estimate from the most comparable state inventory.[25]

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In states such as Ohio, North Carolina, and Indiana, accelerated pipeline repair and replacement programs have resulted from partnerships among companies, states, municipalities, and public utility commissions. A partnership between distribution companies and the Ohio Public Utility Commission, for instance, which sets cost recovery rates for natural gas pipeline repairs, is the reason that Cincinnati, OH, is on track to complete its replacement of pipeline mains by 2015 (the original goal) and of service lines before 2020, based on a linear projection of the data (Figure 2).[23] At the opposite end of the spectrum, replacement rates in Baltimore, MD, have been among the slowest in the United States, with about 140 additional years projected to full replacement based on replacement rates between 2004 and 2013[11] (and acknowledging recent programs in Maryland to speed pipeline replacements). Manhattan falls somewhere in between. There, the New York distribution company maintained a fairly steady rate of 1–2% replacement for both mains and service lines from 2000 to 2014 (with an unusually, and possibly unreasonably, high replacement rate reported in 2013; Figure 2). On the basis of an approximate linear projection of the data in Figure 2, it will take another 26–52 years for mains or 11–23 years for service lines for completion. Between 2000 and 2014 the New York distribution company decreased its portion of mains and service line replacement candidates by 26% and 52%, respectively, a substantial improvement.

Overall, natural gas pipeline safety is improving across the United States, and the miles of distribution replacement candidate pipelines are decreasing. The number of gas pipeline incidents causing death or major injury dropped by half between 1991 and 2011, from about 70 incidents per year on average to around 35.[6] Of the approximate 2,150,000 miles of gas distribution lines (mains and service) in the United States in 2013, 7% of mains and 9% of service lines were replacement candidates in 2013, down from 12% and 14%, respectively, in 2000.[21] In fact for most states, less than 10% of main and service pipelines are now replacement candidates (41 and 35 states, respectively). The greatest concentration of replacement candidate pipelines is in the northeastern United States, where infrastructures are generally older (Figure S3). Continued and sustained progress in natural gas pipeline replacements and repairs, implemented with an eye to detection and cost, will improve safety and air quality and reduce greenhouse gas emissions.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.estlett.5b00213.

> Figure S1 shows the 42 street locations in Manhattan selected for a survey to determine the source of natural gas sources. Figure S2 maps the 145 road miles re-driven at night in Durham, NC, in July of 2015 and the locations with concentrations >2.5 ppm of CH_4. Figure S3 shows United States states with high concentrations of replacement candidate mains in 2013. Tables S1, S2, and S3 present wind speed and weather data during the 2014 driving campaigns for Durham, NC, Cincinnati, OH, and Manhattan, NY, respectively. Table S4 shows results for the source identification survey of Manhattan in July 2015 (Figure S1). Table S5 presents wind speed and weather conditions during July 2015 for the Durham, NC, re-drive of 145 road miles at night (NOAA Quality Controlled Local Climatological Data, Durham, NC, and Raleigh-Durham International Airport, NC, stations). (PDF)

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Notes

The authors declare no competing financial interest.

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