Chapter 27

ANALYSIS OF ELECTRICAL POWER AND OIL AND GAS PIPELINE FAILURES

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Abstract This paper examines the spatial and temporal distribution of failures in three critical infrastructure systems in the United States: the electrical power grid, hazardous liquids (including oil) pipelines, and natural gas pipelines. The analyses are carried out at the state level, though the analytical frameworks are applicable to other geographic areas and infrastructure types. The paper also discusses how understanding the spatial distribution of these failures can be used as an input into risk management policies to improve the performance of these systems, as well as for security and natural hazards mitigation.

Keywords: Electrical power, oil and gas pipelines, risk, count regression models

1. Introduction

The energy infrastructure is required to operate practically every other infrastructure; failures in the energy sector can cascade to other sectors, often creating widespread disruptions. This paper provides an analysis of the vulnerabilities of the electrical power, oil and gas sectors, three major components of the energy infrastructure. For simplicity, we refer to hazardous liquids pipelines as oil pipelines, although they carry other hazardous liquids, e.g., anhydrous ammonia. It is vital to understand the nature of outage trends in the three sectors as a means for identifying areas of specific vulnerability and susceptibility to widespread damage in the event of human-initiated or natural catastrophes.

Evidence over roughly the past decade seems to point to the growing importance of weather-related events as at least partially responsible for U.S. outages. In the electricity sector, the proportion of outages attributed to weather-related events appears to be growing [10, 11]. In the oil and gas sectors, outages in transmission pipelines and production facilities are also often weather-related. For example, the Gulf Coast hurricanes of 2005 resulted in the Colonial pipeline, which serves much of the east coast of the U.S., not being fully operational for

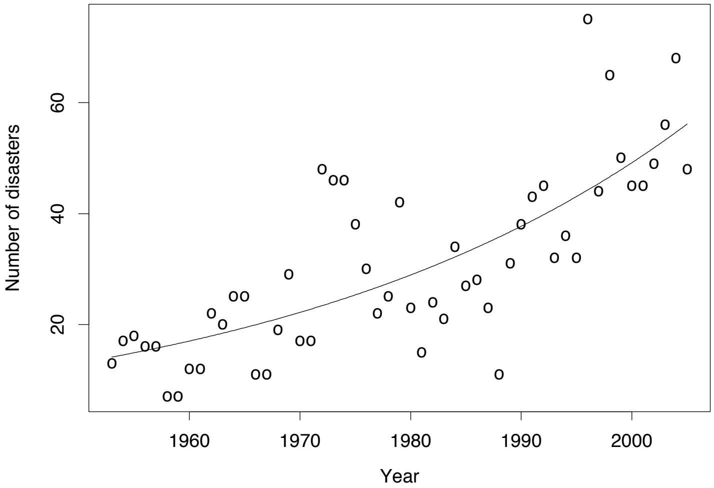


Figure 1. Federally-declared major U.S. disasters (1953 – 2005).

nearly ten days. Several refineries were also non-operational for similar time frames.

According to data released by the Federal Emergency Management Agency (FEMA), natural hazards in general (which include the most severe weather events) have been growing steadily over the past few decades. Figure 1 shows the annual number of federally-declared major disasters from 1953 through 2005, with a negative binomial regression fit superimposed on the counts. The regression model (which fits the data well) implies a 2.7% annual increase in major disasters over roughly 50 years.

Meanwhile, the energy infrastructure and society's dependence on the infrastructure continues to grow, making the ramifications of disruption much more serious. For example, the production of energy in the U.S. doubled between 1950 and 2000 [16] (calculated from [13, 14]).

Given its importance, understanding the extent of vulnerabilities in the energy sector and its resilience to disruptions is critical. An analysis of a hypothetical attack on New Jersey's systems alone found that "the electrical power system's resiliency to damage is the key to the extent and duration of any economic consequences of a terrorist attack, at least in New Jersey" [3] (p. 722).

2. Electrical Power Outages

The electricity infrastructure has become so central to our lives that we take it for granted. It is difficult to think of any daily activities that are not somehow related to electricity. Hence, understanding electrical power outages

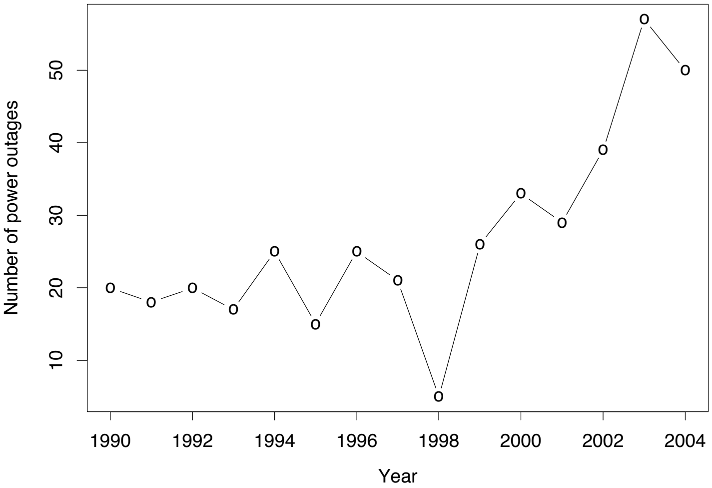


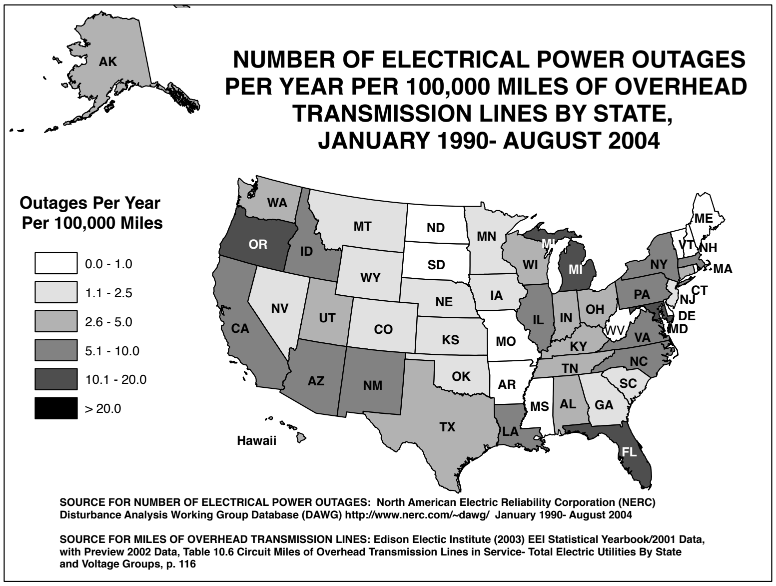
Figure 2. Electrical power outages (1990 – 2004).

and the sector's vulnerabilities is key to maintaining national security. This section examines electrical power outages in the United States using data for the period 1990 – 2004. The data were obtained from the Disturbance Analysis Working Group (DAWG) database, which is maintained by the North American Electric Reliability Council (NERC). The database includes information on 400 outages and is available online [4].

Figure 2 presents annual counts of electrical power outages for 1990 – 2004. It is apparent that other than in the anomalous year 1998, there has been a steady increase in the average annual number of outages. This is consistent with other analyses [7] that found increasing rates, particularly in outages that were confined to a single state.

Although the DAWG database has been used to portray various dimensions of outage patterns and trends [1, 12], analyses of the spatial distribution of these outages and their characteristics are less common. Maps like the one shown in Figure 3 help illustrate the spatial variation. Figure 3 provides the number of electrical power outages per 100,000 circuit miles of overhead transmission lines for January 1990 – August 2004 by state. Note that outages in different states that were related to each other are listed as separate outages.

Electrical power outages are not evenly distributed across the country. As one might expect, states with higher populations and energy use are likely to have more outages. Outages, however, can also vary from one region to another for several reasons, e.g., weather conditions, utility maintenance and investment policies, and the regulatory environment under which utilities operate. Weather events and equipment failure are the most common causes of outages, but the relative importance of different causes of outages has changed over the period


NUMBER OF ELECTRICAL POWER OUTAGES PER YEAR PER 100,000 MILES OF OVERHEAD TRANSMISSION LINES BY STATE, JANUARY 1990- AUGUST 2004

SOURCE FOR NUMBER OF ELECTRICAL POWER OUTAGES: North American Electric Reliability Corporation (NERC) Disturbance Analysis Working Group Database (DAWG) http://www.nerc.com/~dawg/ January 1990- August 2004

SOURCE FOR MILES OF OVERHEAD TRANSMISSION LINES: Edison Electic Institute (2003) EEI Statistical Yearbook/2001 Data, with Preview 2002 Data, Table 10.6 Circuit Miles of Overhead Transmission Lines in Service- Total Electric Utilities By State and Voltage Groups, p. 116

Figure 3. Electrical power outages per 100,000 miles of transmission lines.

under analysis in the United States. In the early 1990s equipment failure was the major cause of outages, but by the early 2000s weather events were the most common cause [11, 17]. This is consistent, of course, with the apparently increasing frequency of natural disasters noted in Section 1.

The states with the highest number of outages were California (56), Michigan (30), Florida (29), New York (26), Texas (22), North Carolina (22), Oregon (19) and Illinois (18). No outages were reported in Delaware, Maine, Mississippi, New Hampshire, North Dakota, Rhode Island, South Dakota, Vermont and West Virginia. Although it seems clear that state size and population are related to the frequency of outages, this is not the only effect, as larger states such as Ohio and Pennsylvania had fewer outages than smaller states such as Oregon.

The observed patterns can be explored more formally. Statistical analyses of incident counts are based on count regression models [9], since the response variable in each case is the number of outages or the number of incidents for each type of pipeline (hazardous liquids, natural gas transmission and natural gas distribution, respectively), in each state in a given year. The standard distributional model for data of this type is the Poisson random variable. Let Y_i be the number of outages (incidents) occurring in a given state during a given year. The Poisson random variable implies that the probability of observing y_i outages (incidents) is

$$P(Y_i = y_i) = \exp(-\mu_i + y_i \log \mu_i - \log y_i!),$$

where μ_i is the expected number of outages (incidents). The Poisson regression model posits a loglinear relationship between μ_i and a linear combination of the predictors,

$$\mu_i = \exp(\beta_0 + \beta_1 x_{1i} + \cdots + \beta_k x_{ki}).$$

In the context of this paper these predictors are indicator variables that identify the different states and the different years. Parameters of the model are estimated using maximum likelihood (analogous to using least squares for regression models based on normally distributed errors). The adequacy of the model can be assessed using the deviance statistic, a goodness-of-fit test that is compared to a χ^2 distribution.

In many cases, a more meaningful analysis occurs if the number of incidents is standardized using an appropriate size measure, as is done in Figure 3. For example, while a larger number of incidents would be expected in states with more miles of pipeline, this might not be as important from a risk management point of view as understanding the rate of incidents per (for example) 10,000 miles of pipeline. Similarly, examining the number of power outages per 100,000 circuit miles of overhead electric transmission lines corrects for uninteresting size effects (such state-by-state figures for 2000 are available in [2]). Modeling the rate is accomplished in the loglinear model by using the logarithm of the number of miles of pipeline or transmission lines as an offset (an additional predictor that is forced to have a slope equal to 1 in the model). So, if t_i is the number of pipeline or transmission line miles in a state, fitting the model

$$\mu_i = \exp(\beta_0 + \beta_1 x_{1i} + \cdots + \beta_k x_{ki} + \log t_i)$$

corresponds to modeling the rate of incidents or outages, rather than the count. All of the count regression models reported in this paper are standardized in this way. Other variables that could be used to correct for size effects include state population size, population density and energy consumption.

The Poisson random variable has the property that its variance is a function of only its mean, i.e., $V(Y_i) = \mu_i = E(Y_i)$. This can be too restrictive, particularly when there are differences in the expected number of incidents that are not accounted for by only the state and year, in that this unmodeled heterogeneity results in overdispersion relative to the Poisson distribution. An alternative model in such a circumstance is a negative binomial regression model (still using a loglinear model relating the mean to the predictors), since the negative binomial random variable has the property that $V(Y_i) = \mu_i(1 + \alpha\mu_i)$, with $\alpha > 0$, which is necessarily larger than the mean μ_i.

A Poisson regression model fitting time and geography main effects fits the 1990 − 2004 power outage data well (a deviance of 666.0 on 713 degrees of freedom, $p = .90$), and indicates strong time and geographical effects. The time trend is consistent with a roughly 8.5% annual increase in outages. States with unusually high numbers of outages per 100,000 miles of overhead transmission lines include California, North Carolina, New York, Oregon, and in particular Florida, Maryland and Michigan (note that this need not correspond exactly to the pattern in Figure 3, since the regression model takes the time effect into account). There is little apparent connection between outage rates and the size of the local power grid, indicating the lack of any economies or diseconomies of scale (Washington, DC, has an extremely high outage rate, but this is somewhat misleading given that it has only three miles of overhead transmission lines).

3. Pipeline Incidents

This section examines the spatial and temporal variation of failures in the hazardous liquid and natural gas pipeline infrastructure. Three data sets are analyzed; a more detailed description of these data sets is found in [8]. The first data set relates to hazardous liquid incidents, which include leaks in pipelines that carry petroleum, petroleum products and anhydrous ammonia. These substances are considered harmful to human health and to the environment. The second data set relates to natural gas transmission incidents, which refer to failures in large pipelines that transport natural gas from facilities that gather, process or store natural gas to large-volume customers and natural gas distribution systems. The third data set relates to natural gas distribution incidents, which refer to failures in the smaller-diameter natural gas distribution pipeline networks that supply natural gas to the final consumer [6]. The data sets are maintained by the Office of Pipeline Safety (OPS), which is part of the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) [5].

It is important to keep in mind that oil and gas transmission and distribution systems also link production facilities, namely, refineries and power plants. As with power plants, refineries are heavily concentrated in certain geographical regions, with more than 50% of U.S. refineries located in only four states [15].

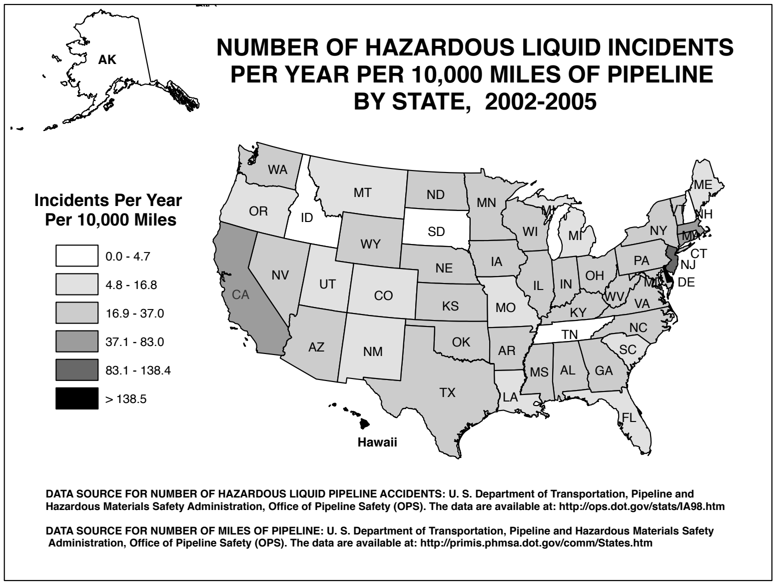
3.1 Hazardous Liquid Pipeline Incidents

Hazardous liquid pipeline incidents are decreasing over time. The overall trend for the period 1986 – 2005 is shown in Figure 4. The sharp increase after 2002 is a result of a change in the definition of what constitutes a reportable incident. Since 2002, spills as small as five gallons have had to be reported to OPS, rather than the 50 gallon limit used earlier.

The spatial distribution of hazardous liquid pipeline incidents also varies significantly from state to state. While some variability from year to year and state to state would be expected just from random fluctuation, a count regression model fit based on main effects for year and state can be used to assess whether the rates of hazardous liquid pipeline incidents differ significantly over time and space. A Poisson model, when fit to the period 2002 – 2005 (this time period is most relevant for current risk management, as it reflects the new definition of hazardous liquid incident), finds both effects highly statistically significant, and fits the data well (the deviance goodness-of-fit statistic is 155.7 on 150 degrees of freedom, with associated tail probability $p = .36$).

The time trend is consistent with a roughly 9% annual decrease in incidents per 10,000 miles of pipeline. Figure 5 illustrates the geographical (state to

Figure 4. Hazardous liquid incidents (1986 – 2005).


NUMBER OF HAZARDOUS LIQUID INCIDENTS PER YEAR PER 10,000 MILES OF PIPELINE BY STATE, 2002-2005

DATA SOURCE FOR NUMBER OF HAZARDOUS LIQUID PIPELINE ACCIDENTS: U. S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Office of Pipeline Safety (OPS). The data are available at: http://ops.dot.gov/stats/IA98.htm

DATA SOURCE FOR NUMBER OF MILES OF PIPELINE: U. S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Office of Pipeline Safety (OPS). The data are available at: http://primis.phmsa.dot.gov/comm/States.htm

Figure 5. Hazardous liquid incidents per 10,000 miles of pipeline.

state) variation. States with notably higher than expected pipeline incidents per 10,000 miles of pipeline are California, Delaware, Hawaii, Kansas, Massachusetts, New Jersey and Oklahoma. States such as California, Kansas and Oklahoma have extensive hazardous liquid pipeline networks and a consistently high number of incidents. On the other hand, Delaware, with only 61 miles of pipeline, had three incidents in 2004. Hawaii also has little pipeline (90 miles), but had one or two incidents in 2002, 2003 and 2004, respectively; similarly, Massachusetts has only 114 miles of pipeline, but had two incidents in 2002 and one in 2003. New Jersey has relatively little pipeline (556 miles), but a steady rate of two to ten incidents each year. Thus, there is little apparent pattern relating higher mileages of pipeline to higher or lower incident rates for hazardous liquids.

3.2 Natural Gas Transmission Incidents

Natural gas transmission incidents dropped dramatically in the mid 1980s. Since that time, incident rates were fairly steady for about 15 years, but they have begun to increase in recent years (see Figure 6). When the data are separated by state and federal designation (Figure 7), the source of the increase in recent years becomes clearer. Incidents involving pipelines with federal designations (i.e., offshore pipelines located outside state jurisdiction) show an increasing trend corresponding to a more than doubling of expected incidents annually after 2002, which accounts for much of the overall increase in incidents. This is supported by formal analysis: a Poisson regression model excluding incidents without a state designation finds little evidence for a time effect, while a model for all incidents implies an increase in incident rates in recent years.

Natural gas transmission incidents also show important geographical variation by state, even after normalizing for the mileage of pipeline in each state. A Poisson regression model fitting time and geography main effects fits the 1986 – 2005 data well (deviance of 911.1 on 950 degrees of freedom, $p = .83$), and indicates a strong geographical effect. Figure 8 illustrates the state to state variation for 2002 – 2005. States with notably higher than expected incidents per 10,000 miles of pipeline include Alaska, California, Louisiana, Massachusetts, Mississippi, New Jersey, Oklahoma, Texas and West Virginia.

Alaska had no incidents from 1986 – 1992, but had one incident in six of the next 13 years, with only 543 miles of pipeline. Massachusetts had one incident in six years and two in one year, with only 1,035 miles of pipeline. New Jersey had incidents in only nine of the 20 years, but when they occurred, in three of the years there was more than one incident (four in 2004), based on 1,436 miles of pipeline. The most common cause of natural gas transmission incidents is damage from cars, trucks or other vehicles. The second most common cause is third-party excavation damage. Together, these account for more than half of all incidents [8]; it seems plausible that such factors are more common in densely-developed areas, as would be typical of the latter two states (Massachusetts and New Jersey).

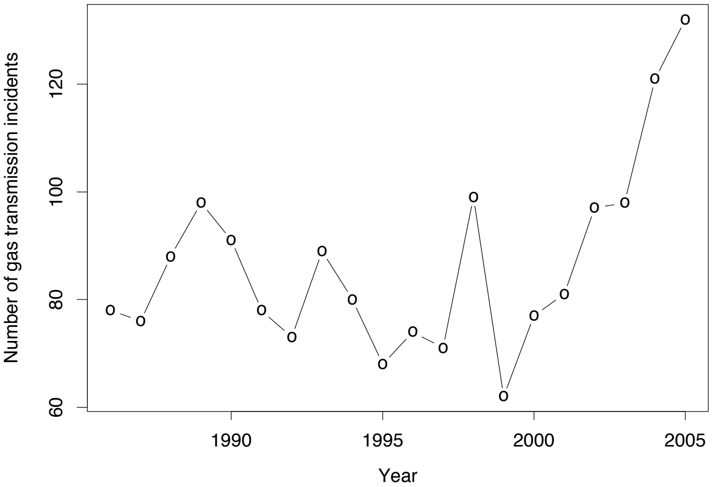


Figure 6. Natural gas transmission incidents (1986 – 2005).

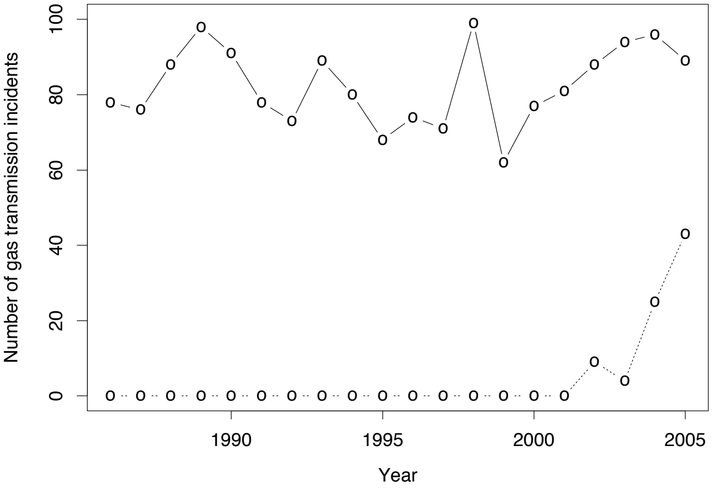
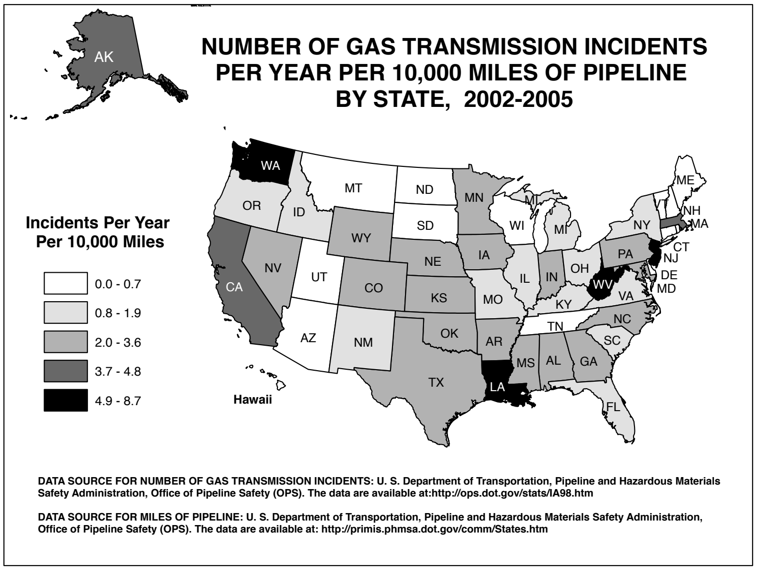


Figure 7. Natural gas transmission incidents (state: solid line; federal: dotted line).



NUMBER OF GAS TRANSMISSION INCIDENTS PER YEAR PER 10,000 MILES OF PIPELINE BY STATE, 2002-2005

DATA SOURCE FOR NUMBER OF GAS TRANSMISSION INCIDENTS: U. S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Office of Pipeline Safety (OPS). The data are available at:http://ops.dot.gov/stats/IA98.htm

DATA SOURCE FOR MILES OF PIPELINE: U. S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Office of Pipeline Safety (OPS). The data are available at: http://primis.phmsa.dot.gov/comm/States.htm

Figure 8. Natural gas transmission incidents per 10,000 miles of pipeline.

California, Louisiana, Mississippi, Oklahoma and Texas are among the states with the most pipeline mileage (in excess of 10,000 miles), implying evidence of diseconomies of scale — the states with the most transmission pipeline mileage also have higher-than-expected incidents per mile of pipeline. While this pattern is strong, it is not universal: Ohio also has more than 10,000 miles of transmission pipeline, but it has a relatively low incident rate. West Virginia also shows up as noticeably unusual; it has a moderate amount of pipeline, yet has had at least one incident in 18 of the past 20 years.

3.3 Natural Gas Distribution Incidents

Natural gas distribution incidents dropped sharply in the early 1980s, but since that time the rate has remained reasonably steady (see Figure 9). The spatial distribution of natural gas distribution incidents, however, still shows important variations between states. Unmodeled heterogeneity in the data results in a Poisson regression model that does not fit the data well, but a negative binomial regression model addresses this and fits well (deviance of 986 on 950 degrees of freedom, $p = .20$). The model finds weak evidence for any temporal (year) effect, but strong evidence for a spatial (geographical) effect.

The state to state variation of natural gas distribution incidents for March 2004 – 2005 is presented in Figure 10. States with unusually high rates of incidents include Alaska, Louisiana, Maryland, Maine, Missouri, Pennsylvania, Texas and Vermont. Maine and Vermont, with relatively low pipeline mileage, had only one or two incidents, but the incidents occurred in multiple years so

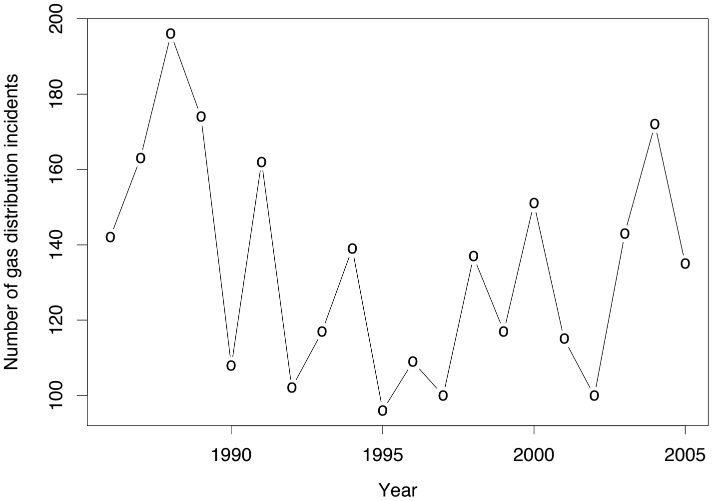
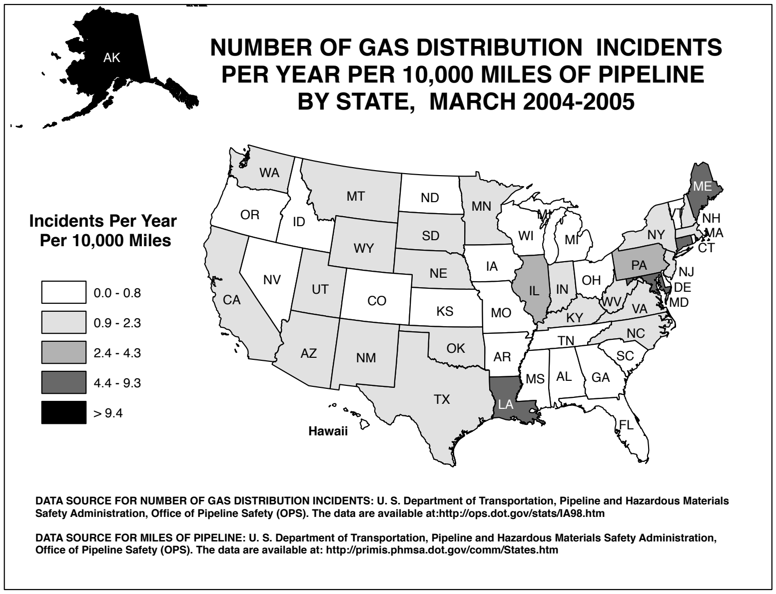


Figure 9. Natural gas distribution incidents (1986 – 2005).


NUMBER OF GAS DISTRIBUTION INCIDENTS PER YEAR PER 10,000 MILES OF PIPELINE BY STATE, MARCH 2004-2005

DATA SOURCE FOR NUMBER OF GAS DISTRIBUTION INCIDENTS: U. S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Office of Pipeline Safety (OPS). The data are available at:http://ops.dot.gov/stats/IA98.htm

DATA SOURCE FOR MILES OF PIPELINE: U. S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration, Office of Pipeline Safety (OPS). The data are available at: http://primis.phmsa.dot.gov/comm/States.htm

Figure 10. Natural gas distribution incidents per 10,000 miles of pipeline.

they cannot be viewed as isolated incidents. Alaska only had three incidents from 1986 – 1992, but has averaged more than five incidents annually since then, with only 2,647 miles of distribution pipeline. The other states mentioned had incidents at a relatively consistent rate over the twenty-year period.

4. Conclusions

The U.S. energy infrastructure shows a high degree of spatial concentration at the state level with respect to electrical power and oil and gas transmission and distribution systems, as well as with respect to outages in these systems. This indicates a potential vulnerability in that a disruption in any given area will have widespread consequences. Our analyses demonstrate that the effects of such concentration can be difficult to predict, since there is consistent evidence of differences in the numbers and seriousness of consequences of electrical power outages and hazardous liquids and natural gas pipeline incidents from state to state. Consequently, it is crucial to understand the underlying causes of these geographic differences, as appropriate risk management strategies would be different in regions with higher rates of incidents (higher risk) compared to those with lower rates of incidents (lower risk).

Similar analyses can be undertaken at the local and regional levels subject to the availability of data. Such spatially-based data would be a critical input to prioritizing areas for targeting resources in risk management efforts.

Incorporating data from the Canadian electrical power grid would be useful, given the interdependencies existing between the U.S and Canadian grids. Data about the outcomes of pipeline incidents (e.g., numbers of customers affected and outage times) would also make the analyses of incidents more informative. Unfortunately, the OPS oil and gas pipeline databases do not contain this data; however, similar data for electric power outages is available [10]. It is also important to conduct analyses that consider the age of infrastructure components, but little, if any, published data on this topic is available.

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