A Few Spills a Year, That's Normal? Learning in the Pipeline Industry

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> The National Transportation Safety Board determines that the probable cause of the pipeline rupture was a pressure surge initiated by the automatic shutdown of a pump station caused by the dispatcher's delay in getting it started, followed by his attempt to relieve the surge pressure into a stub-line connection instead of following the company procedure of shutting down all of the pumps on the line (NTSB 1981).

> [T]he NTSB concludes that although Enbridge had procedures that required a pipeline shutdown after 10 minutes of uncertain operational status, Enbridge control center staff had developed a culture that accepted not adhering to the procedures (NTSB 2012).

The pipeline industry in the US and its regulator have made great efforts over the last 40 years to improve pipeline safety, cutting the spill volume per barrel-mile transported more than in half (see Figure 1).[1] Yet, a 1970s critic of the Trans-Alaska Pipeline System would be as correct as a current critic of the currently planned Keystone XL pipeline in saying this infrastructure remains inherently dangerous. Since the turn of the millenium, in the area of refined petroleum pipelines, efforts to make pipelines more safe have bottomed out, and gains in the safety of crude pipelines have been offset by a growth of the network and increase of utilization. In other words, there are more pipelines, therefore, there are more spills. Is it possible at all to remove the risks of environmental damages from a technology with catastrophic potential? *What are the limits to organizational and population level learning?*

[1] A barrel-mile is one barrel of oil transported over one mile. Hence, ten gallon-miles could describe either one gallon transported over ten miles, or ten gallons transported over one mile. This method of standardizing oil transport has the advantage that it takes into consideration both the extend, and utilization of a pipeline network.

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Convergence of organizational learning efforts has been observed as early as the 1930s (Wright 1936). Argote summarizes this literature: "As organizations produce more of a product, the unit cost of production typically decreases at a decreasing rate" (Argote 2013b, p. 1), and this relationship (the *learning curve*) has been found to hold for many other outcome variables that organizations care about. The relationship between experience and unit cost is great news for organizations that seek to increase profits. However, the notion that there is a limit to to this relationship could spell bad news with regard to environmental pollution.

With dissertation, I contribute (1) to the literature on *grand challenges* (George, Howard-Grenville, Joshi, & Tihanyi 2016). I am taking stock on the current levels of chemical pollution caused by the pipeline industry. Chemical pollution is identified as one of the nine areas of human impact that potentially infringes on our planet's safe operating boundaries (Rockström et al. 2009b). The effort to explore management of environmental pollution is motivated by a call of George, Schillebeeckx, and Liak (2015) for an investigation of theories of technology adoption and their implications for our use of decreasing natural capital. (2) In service of discussing resource use, this dissertation reconnects existing knowledge on the behavior of organizations (Cyert & March 1963), with more recent developments in organizational learning. In particular, Levitt and March (1988) propose a model of organizational learning that goes beyond the learning curve *and* derived theories that seek to decompose learning (e.g., Argote 2013b, p. 2). Relevant for the phenomenon at hand, the authors conclude that "[t]he same processes that that yield experiential wisdom produce superstitious learning, competency traps, and erroneous inferences" (Levitt & March 1988, p. 335), and propose ways to address these issues. This dissertation talks to the limits of organizational and population level learning, with that cautious note in mind.

This dissertation employs both quantitative and qualitative data. (1) The first chapter juxtaposes qualitative evidence for learning past the turn of the millenium with a bottomed out or leveled off learning curve (where learning proceeds only at a very slow pace) for refined petroleum pipelines. What leads to a learning curve bottoming out in that fashion? The quantitative data available on the pipeline industry includes the extent of individual pipeline operators' networks, and the pipeline spills stemming from those networks. This data also allows us to track the elimination of certain spill types. The qualitative archival data reveals the complexity and interactions that lead to pipeline spill (such as staff not always following procedures, as exemplified by the introductory quotes), which are difficult to eliminate. (2) The second chapter combined two different literatures on learning to lay out the theoretical underpinnings of the bottoming out process. (3) The third chapter uses qualitative data to analyze the microfoundations of learning bottoming out.

Literatures

Multiple literatures contribute to this dissertation. The challenge will be to make these languages talk to one another. The literature on *Grand Challenges* provides us with a research agenda, but has little to offer (so far) that can guide our work (George et al. 2015). In lieu of input from management research on the use of natural resources, we can draw on works in interdisciplinary journals that discuss use of *natural resources* by organizations (e.g., Rockström et al. 2009a). For theory development, this dissertation builds on the learning literature. The *learning literature* again falls into two camps: (1) One stream traces back to the research on *learning curves.* This stream looks to disaggregate organizational learning and identify the factors that accelerate or impede learning (Argote 2013a). (2) The other stream originates in the *behavioral theory of the firm.* That stream looks at choices and systemic impediments to learning (e.g., Cyert &

March 1963, Levinthal & March 1993, Levitt & March 1988). Beyond these literatures, *pipeline technology* is discussed in engineering, a stream of sociology conducts *disaster research*, and research on complex systems (especially Perrow 1984) also contributes to this dissertation. These literatures will play a subordinate role.

Organizational learning

As mentioned above, the literature on organizational learning traces its roots back to two distinct streams of literature that can be distinguished by their definitions of learning. The first stream defines learning as "a change in the organization's knowledge that occurs as a function of experience" (Argote & Miron-Spektor 2011, p. 1124). Henceforth, this stream will be called the knowledge-based approach. The second literature holds that organizations learn "by encoding inferences from history into routines that guide behavior" (Levitt & March 1988, p. 320). The contributors are much more careful about stating that organizations *know* per se the lessons learned. Henceforth, this second stream of literature will be called the behavioral approach.

Knowledge-based approach. The first discussions of organizational learning are found in the learning curve literature (Wright 1936). In particular, WW2 provided a couple of "quasi-experiments". In the shipbuilding industry, the researchers could observe how with every subsequent unit of production, productivity would improve (Searle & Gody 1945). The most straightforward mathematical representation of the learning curve is the progress ratio. For instance, if the progress ratio is p, then each time the cumulative output doubles, the unit cost would be predicted to drop to $p\%$ of its previous value (Argote 2013b, p. 15). In other words, while in the beginning organizational learning allows for a quick reduction of unit cost, eventually, the next doubling of cumulative production is so far out that the unit cost is almost constant. One ambition of the learning curve literature is to mathematically disaggregate learning curves into multiple intraorganizational factors that predict the speed of learning (e.g., Arrow 1962).

Because so many different factors were found to influence the learning rate, the literature eventually directed its attention to the process of organizational learning itself. A large share of this body of work roughly follows this pattern (taken from Love, Roper, & Vahter 2014): the author selects an organization-level performance variable (innovation, measured as sales from newly introduced products), and gathers this data for large companies in an industry or country (Ireland). Then, independent variables are selected that account for the heterogeneity across organizations (innovation linkages, measured as product development with customers or suppliers, joint ventures, etc.). This approach has allowed researchers to identify a broad variety of sources of variation (Argote 2013b, pp. 18ff).

A limitation of this relatively formulaic approach however is that it may fail to identify path-breaking innovation. Not all knowledge is equally important, and the best insights are sometimes difficult to capture with quantitative metrics. For instance, some new pieces of knowledge might fall outside the regular schema of innovation and lead an organization into a new industry. And many fossil fuel companies are currently (still) successful because they double down on their existing knowledge stock and insulate their industry from changes–an orthodox learning paper might still diagnose learning, if, for example, production increases. But an example of a more interesting question with regard to learning would be which organizations manage to diversify and benefit from the rise of renewable energy.

Behavioral approach. The Carnegie school early on took notice of organizational learning (e.g., Cyert & March 1963). For some time, this literature developed in parallel to the learning curve literature. This difference between the two approaches is best exemplified by Argyris and Schön (1978). Argyris and Schön (1978) developed the concept of double-loop learning. The first loop represents adjustments according to well-known decision criteria, such as launching a promotion when a sales goal is not met. The second loop represents an adjustment of the decision making process itself. For instance, a member of the organization may discover that the organization's goal has become unattainable, and push for a modification of the goal itself. This literature allows scholars to talk about issues that fall outside the scope of the learning curve (and knowledge-based) literature. A drawback is that it is difficult to translate the this literature into empirical work. For example, one major criticism of learning curves is that findings may have resulted from a self-fulfilling prophecy–an organization ends up at a certain productivity level *because* that productivity level was the goal. The organization would not overaccomplish, because members lower their efforts when they approach the target. And if the organization falls short of its goal, the organization may move the goal post–by adjusting the goal, or its accounting approach.[2] The behavioral approach provides us with a language to discuss these issue and similar issues.

Concepts that speak to the phenomenon of pipeline spills include the aforementioned double-loop learning, exploration and exploitation (March 1991), the competency trap (Levitt & March 1988), and experiential learning under ambiguity (March & Olsen 1975). Some streams of the behavioral approach have cross-fertilized the knowledge-based stream. These include work on learning from rare events (March, Sproull, & Tamuz 1991, Maslach, Branzei, Rerup, & Zbaracki 2018), and learning from failure (e.g., Madsen & Desai 2010). These literature talk to some of the tensions that can be observed with regard to pipeline safety–an insistence on existing technology, and a lack of major overhauls, but also surges in activity in response to spills.

Data and Methods

There are two main sources for data on pipeline spills in the US. (1) The Pipeline and Hazardous Materials Safety Administration (PHMSA) maintains a repository on all pipeline spills that occur. A fairly unique attribute of the data is that there is both qualitative and quantitative data available. Over 300 pipeline spills occur in the United

[2] Similarly, the reason why organiztional learning and learning curves appear to be omnipresent could be a result of a publication bias.

States every year, and more than 100 of them are classified by the PHMSA as significant.[3] The number of spills is sufficient for quantitative analysis to be sensible, but not at a level where the individual spill becomes meaningless as a unit of analysis. For spills that occurred in 2002 and after, the data quality is generally good, as minor spills typically do not result in fines, but failure to provide information on a spill to PHMSA does carry a fine.[4] PHMSA also provides a dataset on pipeline operators, which allows for identification of the organzation that caused an oil spills, and how many miles of pipelines these organizational operate.[5].

(2) The National Transportation Safety Board (NTSB) provides reports on pipeline spills that the agency deems significant. These reports typically have a length of 50-200 pages (usually being more than 100 pages long) and detail the incident, the events leading up to it, and its causes. From 1969 until today, 142 reports and briefs have been published. What makes these reports significant is that NTSB tries to identify these incidents early on, and appear on the scene as early as possible. They spend significant resources to observe the spills as they happen, and investigate the underlying causes (rather than liability) of the spills afterwards.[6] On a side note: the NTSB in its reports frequently criticizes the PHMSA.

PHMSA is the primary source for quantitative data, and NTSB the primary source for qualitative data. The NTSB reports are (obviously) biased toward very serious incidents, and the qualitative data available on less serious incidents is much less detailed.

[3] Meaning an injury, fire, explosion or property damage of over $50,000, or the spill volume is at least 50bbls. See also `https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/docs/pdmpublic_incident_page_allrpt.pdf` and `https://julianbarg.shinyapps.io/incident_dashboard/`, accessed 2020-07-14.

[4] For instance, up to $1,000,000 for a failure to immediatly update PHMSA, see `https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/docs/subdoc/3976/gdincidentinstructionsphmsa-f-7100-12014-10-through-2019-04.pdf`, accessed 2020-07-14

[5] See `https://github.com/julianbarg/oildata`, accessed 2020-07-14

[6] For instance, in one case NTSB tried to replicate an error of a SCADA system on a replica of the original SCADA setup (NTSB 2002), and in another case NTSB used various pieces of heavy equipment on a pipeline section to determine what caused the mechanical damages that lead to a spill (NTSB 1990).

Only to some degree, this dearth of information can be counterbalanced by additional research on incidents that are not covered by NTSB, as some incidents are not reported on by any other source except for PHMSA. This lack of information on spills that are perceived as less impactful is a known limitation of research on pipeline spills. Both NTSB and PHMSA also have an overt focus on the direct impact of oil spills. The PHMSA dataset focuses on quantitative attributes of the spill, such as spill volume, volume of recovered oil, and boolean variables on remediation, whereas the NTSB focuses on the immediate impact, such as the magnitude of resulting fires, the number and types of injuries that occurred, and the immediate property damages caused. The PHMSA and NTSB data on the impact needs is supplemented with reports from residents, which both provide an understanding of the impact that the spills have on their lives, and provides a more tacit understanding of the impact on the local ecosystem. And of course the collection of third party data serves to triangulate information.

The qualitative and quantitative information provides us with three kinds of insights. In the first chapter, I carry out a panel regression to assess the state of organizational and population level learning in the pipeline industry. The qualitative data that is consulted indicates that specific issues are addressed through learning, but new, unique problems keep appearing, which prevents the industry from making further progress. The second chapter will not present any data, but rather discusses the learning literature while only sporadically touching on the phenomenon at hand. The third chapter uses discourse analysis and nonparticipant observation to explore the microfoundations of a coexistence of learning and a bottomed out learning curve.

Chapter 1: Stuck on Innovation

Organizational learning comes down to choices. Firms can either invest in improving existing technology, or develop new technology (March 1991). Investing in the "wrong" technology can lead to technological lock-ins (Levinthal & March 1993). The actors in the pipeline industry have selected a number of technological solutions to resolve their most pressing issue. When a pipeline spill occurs, the oil quickly infiltrates the soil and seeps into the groundwater.[7] The environmental degradation caused by oil affects the local environment, and the local populace, too: a 2019 sibling comparison study on oil spills in Nigeria found that in localities that are affected by oil spills, for every 1,000 live births, an additional 38.3 neonatal deaths occur(Bruederle & Hodler 2019).

In their fight against pipeline spills, pipeline operators employ a variety of technologies, such as smart pigs, leak detection systems, and SCADA systems. Smart pigs, while traveling through the pipes, utilize electromagnetic flux or ultrasonic probing to assess corrosion or mechanical damages to the pipe (Singh 2017). Internal leak detection systems measure the flow of oil at two points A and B to detect any loss in between those points. External leak detection systems detect signs of escaping hydrocarbons, and include acoustic, hydrocarbon, and temperature sensors. (Shaw et al. 2012). SCADA systems are systems that allow an operator remotely monitor and operate lines. The operator typically sees on his screen charts of the flow at different points, can open and close valves, and startup or shutdown delivery of oil. Alarms from leak detection systems of the line are also displayed to the SCADA operator.[8]

The high technology character of leak detection stands in contrast to the experienced reality of pipeline spills. A 2012 study commissioned by the Pipeline and Hazardous Materials Safety Administration (PHMSA) of onshore pipeline spills that occurred over a 19 month period, SCADA systems assisted in less than 25% of cases with the detection and confirmation of the spill (Shaw et al. 2012, p. 3-33). In only 17% of cases was the operator or SCADA system listed as the initial identifier of the leak, while the public or emergency

[7] The infiltration depth in sand is assumed to be over 10m in the first day alone (Bonvicini, Antonioni, Morra, & Cozzani 2015).

[8] Larger pipeline companies operate control centers where all lines in a region are managed. Operators usually operate multiple SCADA systems at once, and more experienced employees supervise the operators. Control centers are operated in formal hierarchy, where for certain operations (such as clearing an alarm), a SCADA operator will require the go-ahead from a supervisor. See NTSB (2012) for an in-depth description of an Enbridge control center in Edmonton as of 2012.

responders identified 30% of leaks (Shaw et al. 2012, p. 3-39). Why do the great learning efforts by pipeline operators fail to deliver the safety improvements that one would expect to see? A 2012 report prepared by the National Transportation Safety Board (NTSB) on the Kalamazoo River oil spill provides a good starting point for understanding the problem. A regional manager of Enbridge is quotes as saying: "...I'm not convinced [that there is a problem]. We haven't had any phone calls. I mean it's perfect weather out here–if it's a rupture someone's going to notice that, you know and smell it" (NTSB 2012, p. 100).

This chapter uses the quantitative data from PHMSA to demonstrate how existing problems are addressed, following major spills that catch the attention of the industry, the regulator, and the public. That empirical observation is contrasted with the character of the two challenges that remain: (1) as holes are plugged, new unique sources of spills, for example climate change-related weather changes, emerge. (2) Both the "human factor" and the "organizational factor" are pervasive factors that yet to be completely eliminate as sources of error in any context. Overall, the geographic, technological, and organizational complexity of pipelines have led to the current situation, a quasi-standstill in the sector for refined oil. Crude oil pipelines on the other hand still have some potential for improvements, as simple and fundamental problem of this sector– the corrosiveness of the commodity– is addressed through new coatings, and cathodic protection.

The quantitative section of this chapter uses a sample consisting of the 100 largest operators in the pipeline industry over the period from 2004 through 2019. The data that is available from PHMSA is matched and supplemented with data from Compustat. This quantitative section focuses on improvements over time in organizations affected by a specific source of incidents, and a reduction in certain causes of spills. Some qualitative data supplements the quantitative analysis by showcasing the processes of population level learning (Miner & Anderson 1999), especially for crude pipelines. The qualitative section then uses archival data to explore a sample of 15 major pipeline spills since 1986 to contrast the specificity of learning in the quantitative analysis with the complexity of the systems that the incidents occur in, and the complex interactions that lead to spills. The sample of 15 spills includes the top three spills with regard to spill volume, net loss (spill volume minus volume recovered), number of injuries, number of fatalities, and property damage. This sampling method ensure both a variety in the type of spills, and a good availability of archival data.

This chapter contributes to the literature on knowledge-based learning by exploring the topic of a bottomed-out learning curve through raising the issue of aggregate and specific learning. The chapter also contributes to the debate on industry resource use: it discusses both the historical development and the potential future reduction (or lack thereof) of an industry's environmental footprint. Whereas in the past, improvements were made through incremental learning in the form of development of new technology, the analysis suggest that further improvements may only be possible through bold, maybe costly new choices, including a change of industry for some companies.

Chapter 2: Theoretical Foundations of Learning

This literature review focuses on organizational learning. The purpose of this chapter is to shed light on the intricacies of learning in the pipeline industry from a theoretical perspective. The first section summarizes the literature of the knowledge-based approach. In particular, the section emphasizes the strength of the knowledge-based approach, which accurately describes the accumulation of a knowledge stock that does take place in an organization when the goal is more or less clear and the environment stable. Further, This first section summarizes some of the other accomplishments of the literature that roughly fall into the knowledge-based stream, specifically its predecessor the learning curve literature, as well as vicarious learning, and population level learning.

The second section summarizes the behavioral approach to organizational learning. In particular, this section highlights the gaps left by the knowledge-based approach that may be filled by work in the behavioral space. The behavioral approach appreciates the nonlinearity and messiness of learning. Significant learning can results from individuals or groups organization that seek for the organization to break with convention (Argyris & Schön 1978). This form of learning poses a challenge to the knowledge-based literature, because the changes that take place fall outside the normal rubric of improvement (as exemplified by learning curves). Other examples of these qualitatively different dimensions of learning in the literature are exploration and exploitation (March 1991), and high intellect vs. low intellect learning (March 2010).

Building on the review of the two approaches to learning, this literature review then discusses two critical issues, which become particularly important in the context of pipeline spills. First, in light of the leveling off of the learning curve (which in the pipeline industry takes the shape of a "baseline" of spills, or "normal accidents" Perrow 1984), this section addresses the merits of less complex technologies. The learning literature is implicitly technocentric, but when efficiency does not take the primacy–as is the case when dealing with toxic chemical such as oil– rather than adding and improving technologies, scaling back and relying on less complex technologies may be a better way to go.

Second, in light of the damages that have been brought about by the petroleum industry, it is timely to take a critical look at the modernistic assumptions of the learning literature. The learning literature should confront the fact that new technolgies also routinely bring about new problems (Beck 1992). To stay with the theme of this dissertation: pipeline spills (and climate change) are problems that did not exist before the petroleum industry came into being. Acknowledging the conjunction of technology and risks is not meant to take away from the recognition of its merits. Yet, we encourage a debate about the tendency of the literature to equate "newer" with "better" rather than "different".

Chapter 3: The Microfoundations of Learning Stagnation

The first chapter revealed a leveled-off learning curve in the pipeline industry, as far as refined petroleum pipelines are concerned. This third chapter of my dissertation explores the microfoundations of this leveled off learning curve. Somehow, efforts to improve technology and learn from occurring spills coexists with a lack of improvements in pipeline safety on the population level. To explore this phenomenon, this chapter turns to qualitative data.

Two types of data provide access to this phenomenon. (1) A discourse analysis reveals how the industry, at a population level, shields itself from a discovery (by an outside audience) of the lack of improvements. To do so, population level organizations like the American Petroleum Institute (API) emphasize metrics that show the industry in a good light. The regulator also plays an important role in the process. Members of the industry like to emphasize their adherence to the "world class" American regulations to shield themselves from criticism. At the same time, the evaluation of its main regulating body, the Pipeline and Hazardous Materials Safety Administration (PHMSA), depends on the safety performance of the industry. In other words, this regulating body would also suffer from an appearance of the industry as being unsafe. To obtain a positive performance evaluation from its stakeholders–the Department of Transportation, the United States Congress, and ultimately the American public–PHMSA needs to show either that the industry is safe, or (when the industry cannot be presented as safe because high profile incidents occurred in the recent past) that PHMSA and the industry addresses safety problems. In other words PHMSA also has an interest in giving the appearance of learning, over a big-picture analysis of the industry's performance. Finally, NTSB's mission is directly related to learning–the organization was created to analyze transportation-related incidents and define lessons to be learned. The interest of the involved parties in highlighting learning over a big picture analysis of safety performance are explored in a discourse analysis.

Non-participant observation is a potential supplement to the discourse analysis.

When the EPA, PHMSA, or coast guard responds to a pipeline spill, over the course of a few days, an important process takes place. Qualitative data indicates that emergency respondents reaction to pipeline spills is often shock. But when the EPA presents its response to pipeline spills (and other pollution events) to the public, the agency emphasizes its ability to carry out environmental remediation. Similarly to the process that the discourse analysis reveals, in the field emergency respondents go through a process of translating an inherently negative event (pipeline spills) into an event where the agency shows positive action. The qualitative data collected for this chapter allows for a further analysis of the microfoundations of a leveled off learning curve, where learning specific lessons coexists with aggregate stagnation.

Conclusion

Over the last five years, some debate has taken place in the management literature on our use of decreasing natural capital, under the umbrella of grand challenges. This dissertation contributes to that literature, by raising the issue of chemical pollution, and alleviation of impacts. In lieu of a great lot of literature on this issue in the management literature, this dissertation turns to *organizational learning*, a literature that has discussed related problems for some decades.

The purpose of this work is twofold. On the one hand, it brings attention to the great knowledge stock that exists in management research research on organizational learning and the behavior of organizations, which may benefit further discussions on alleviation of impacts, and use of decreasing natural capital in general. On the other hand, by bringing attention to the systemic issues that are highlighted by the grand challenges literature, this dissertation also provides a new direction for research on organizational learning. An empirical analysis of learning on the organization level would have likely overlooked the lack of aggregate learning that exists in parts of the pipeline industry (with regard to refined petroleum pipelines). The grand challenges literature here provides an important impulse to revisit some assumptions.

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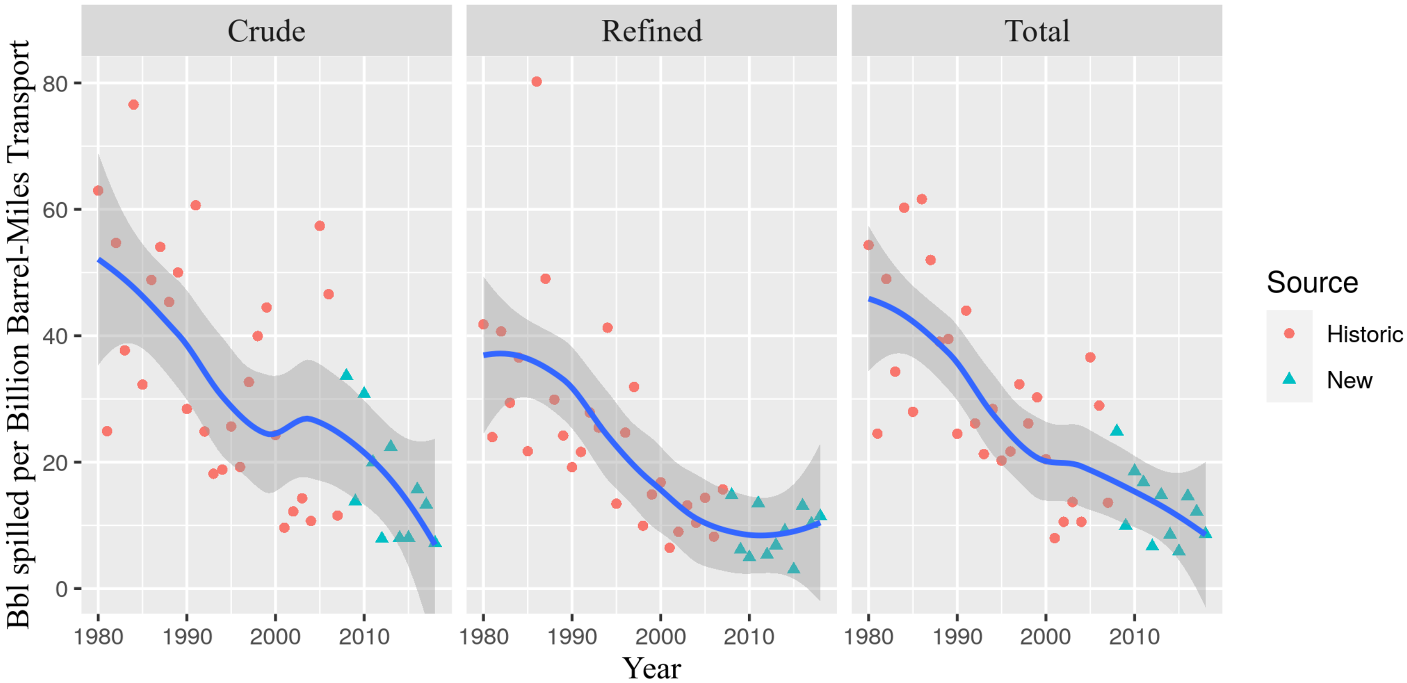
Figure 1. Pipeline safety improvements at the industry level



Blue line:	Local regression (Loess), with confidence interval.
Source (new):	https://github.com/julianbarg/oildata
Source (historic):	http://www.api.org/environment-health-and-safety/clean-water/oil-spill-prevention-and-response/~/media/93371EDFB94C4B4D9C6BBC766F0C4A40.ashx, p. 38