Gas Distribution Integrity Management: Risk Management Framework

Prepared by:
University of California, Berkeley
Samer Madanat, PhD,
Robert Meade,
Aditya Medury,
Josh Sheeherman

Prepared for:
Joseph Mallia, Project Manager
Northeast Gas Association|NYSEARCH
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I. Executive Summary

The Department of Transportation’s Pipeline and Hazardous Materials Safety Administration (DOT/PHMSA) is encouraging the application of the concepts of risk management by the US gas distribution industry. DOT/PHMSA has not defined a preferred approach, but is placing the burden of defining the details of risk and integrity management upon the industry and ultimately upon each individual company. When integrity management for distribution pipelines was first conceived, the emphasis was upon the management and mitigation of age related processes that might be responsible for pipeline deterioration. Extensive collaboration between PHMSA and the gas distribution industry resulted in greater emphasis being placed upon the reduction and elimination of excavation damage – as a tactic to reduce incidents.

The Integrity Management approach was designed to promote continuous improvement and the investment in risk reduction measures beyond existing regulatory requirements. Implementation of a Distribution Integrity Management Plan (DIMP) is recognized to begin with an iterative process. The plan that is initially implemented is expected to establish a foundation for continuous improvement.

Many other industries are managing aging infrastructure and they have turned to infrastructure and risk management concepts, to facilitate decision-making. As illustrated through their experience, success is highly dependent upon appropriately matching modeling and data processing approaches with the type, extent and availability (in a digital format) of information about the infrastructure. Their journeys typically began by utilizing ranking methodologies to facilitate decision-making. However, the limitations of the approach were soon discovered (inaccurate budgeting, poorly assessed risks and improper quantification of priorities), which eventually led to these industries adopting optimization tools to assess risks and identify priorities. In many cases, this transformation was brought upon through
extensive collaboration of the industries with the federal government, as demonstrated by the
development of the bridge management system, and sometimes as a result of infrastructure failure.

Within the discipline of optimization, there are two fundamentally different strategies available to
process information, order knowledge and break down the decision-making process into stages. This
study recommends the implementation of the ‘top-down’ optimization approach. In the top-down
approach, aggregate maintenance and replacement decisions are made first at the system level, then
translated into decisions for individual facilities (pipe segments) through the definition of classes (which
are very similar to the concept of a region proposed by PHMSA). Based on the current limitations of
data availability, this is the only realistic and feasible approach. Another factor favoring the top-down
approach, especially for the initial stages of DIMP implementation, is the use of expert opinion. In the
absence of substantial data, the knowledge of experts is often used to contribute to the initial estimates
of information about the network.

In addition to identifying a risk management approach and providing its formulation, guidelines for
its implementation are provided – along with a comprehensive identification of lessons learned from
other industries, in their implementation of risk and infrastructure management systems.
II. Introduction

The Department of Transportation’s Pipeline and Hazardous Materials Safety Administration (DOT/PHMSA) has been motivated by its Office of Inspector General and then by Congress to apply the concepts of risk management to the US gas distribution industry. To achieve this goal, DOT/PHMSA has introduced a series of changes to pipeline safety regulation that would require that pipeline operators assess the risks that result from threats, to individual pipe segments in their network (such as from age-related pipe material degradation, third party construction), and then take actions to reduce the resultant risks.

The regulation requires that the industry would build a repository of data and use it in conjunction with ‘integrity’ or risk management techniques to justify the priorities in their capital investment plans (pipeline replacement), O&M expenditure and safety activities as well as to demonstrate that specific allocation of resources would mitigate the identified risks.

While the use of integrity management systems are now required, the DOT/PHMSA is placing the burden of defining the details of integrity management approach upon the industry and ultimately upon each individual company (who must create, implement and continuously improve a company specific integrity management plan).

DOT/PHMSA would like to promote continuous improvement in all safety-related processes in a manner that they can audit, evaluate and ultimately motivate change and improvement on an individual company basis. They have established new reporting requirements and an obligation on the part of operating companies to critically evaluate their processes (in a manner that is open to DOT/PHMSA review).
In parallel with DOT/PHMSA’s initiative, individual state pipeline safety regulators (who bear the responsibility for regulation enforcement on a state level) have been reviewing the proposed risk management construct and have introduced important constraints of their own (through comments provided by their national association). They have raised concerns about the impacts of costs of the proposed program upon the customer, suggesting that some method of cost-benefit analysis would need to be incorporated into the emerging risk management system.

Issue about data has been raised by all stakeholders, many times. Data and understanding its relationship to modeling is the key to deriving value from risk management. The basic assumption of DOT/PHMSA is that more data would be needed. But, actual requirements have yet to be defined.

DOT/PHMSA’s expectations (that the allocation of current resources would consider future risks) combined with NARUC’s expectations (that resources would be allocated in a manner that simultaneously minimizes costs and risks) establishes very demanding requirements for a risk management model. Sophisticated models cost more to purchase and implement and if value is to be derived from such investments – they require more and better data.

The rate at which risk management models can be implemented, the accuracy of their results and the value obtained (risk and cost minimization) may all be dependent upon data – the amount and accuracy of historic data and the ability to collect or accurately estimate new information. This suggests that there may be a dynamic between the value derived from a risk management model and the data available to it and that this dynamic may strongly influence individual company implementation plans.
III. Regulation Review

The integrity management (IM) approach is designed to facilitate the following:

- The allocation of limited, discretionary resources (capital, O&M) to yield a reduction in the public’s exposure to risk. And, in particular, a continuous reduction in excavation damage.
- Regulatory review of an individual company’s approach, and its evolution, through the creation of IM Documentation.
- Long-term, continuous improvement of systems and work processes employed to attain risk reduction goals.

Philosophically, distribution pipeline integrity management is similar to the transmission pipeline IM approach, as both approaches were conceived simultaneously by Congress over ten years ago.

A. Excavation Damage

When integrity management for distribution pipelines was first conceived (in the 1999-2000 time frame) the emphasis was upon the management and mitigation of age relate process that might be responsible for pipeline deterioration. Extensive collaboration between PHMSA and the gas distribution industry (between 2001 and 2009) resulted in greater emphasis being placed upon the reduction and elimination of excavation damage – as a tactic to reduce incidents.
**B. Continuous Improvement**

At its basic level, integrity management is an integrative process consisting of risk analysis, the implementation of action to mitigate risks, complemented by the continuous monitoring and evaluation to identify the effectiveness of these risk mitigation strategies.

The IM approach was designed to promote continuous improvement and the investment in risk reduction measures beyond regulatory requirements.

PHMSA has indicated that the effectiveness of a company’s IM program should be evaluated on an on-going basis (informally). A structured evaluation of DIMP is required every 5 years, as a minimum. A formal evaluation should identify characteristics of an existing IM program that need to be improved and propose changes that would improve program effectiveness. The ultimate goal is improved safety, and, improvement cannot be realized without change – thus continuous monitoring, evaluation and improvement is one of the core elements of the DIMP plan.

**C. Implementation**

Operators should identify pipeline attributes and threats to their pipelines. Further operators should understand implications of these threats and their consequences – for the purpose of applying safety resources that are commensurate with each threat.

Experience has shown that incidents are most often caused by a combination of circumstances – threats that might pose risk to one pipeline may not apply to other pipelines. Thus IM regulation requires that operators evaluate their pipeline to identify unique situational risks and take appropriate actions to mitigate these risks.

Integrity management regulation for distribution operators, thus, requires that operators conduct a comprehensive evaluation of its system by assembling existing (distributed) records, collecting the
insight of their operational staff and expanding data collection efforts in the future (if needed – when gaps are identified).

- An operator must demonstrate an understanding of its gas distribution system, which:
  - Identifies the characteristics of the pipeline’s design and operations and the environmental factors that are necessary to assess the applicable threats and risks to its gas distribution pipeline.
  - Considers the information gained from past design, operations, and maintenance.
  - Identifies additional information needed and provides a plan for gaining that information over time through normal activities conducted on the pipeline (for example, design, construction, operations or maintenance activities) but does not entail extraordinary effort.
  - Develops and implements a process by which the IM program will be reviewed periodically and refined and improved as needed.
  - Provides for the capture and retention of data on any new pipeline installed. The data must include, at a minimum, the location where the new pipeline is installed and the material of which it is constructed.
- The operator must consider the following categories of threats to each gas distribution pipeline:
  - Corrosion,
  - Natural forces,
  - Excavation damage,
  - Other outside force damage,
  - Material, weld or joint failure (including compression coupling),
o Equipment failure,
o Incorrect operation, and
o Other concerns that could threaten the integrity of its pipeline.

- An operator must consider reasonably available information to identify existing and potential threats. Sources of data may include, but are not limited to:
  o Incident and leak history,
  o Corrosion control records,
  o Continuing surveillance records,
  o Patrolling records,
  o Maintenance history, and
  o Excavation damage experience

While performance through people has been eliminated, a requirement in the final rule includes inappropriate operation as a risk that must be considered.

Implementation of DIMP is recognized to begin with an iterative process. A program is to be implemented within 18 months but it is not expected to that all problems will be identified and resolved within this period.

D. Risk Assessment & Management

An operator must evaluate the risks associated with its distribution pipeline. In this evaluation, the operator must consider:

- Each applicable current and potential threat,
- The likelihood of failure associated with each threat, and
• The potential consequences of such a failure.

An operator may subdivide its pipeline into regions with similar characteristics (e.g., contiguous areas within a distribution pipeline consisting of mains, services and other appurtenances; areas with common materials or environmental factors), and for which similar actions likely would be effective in reducing risk.

Finally, an operator must identify and implement measures to address risks that are designed to reduce failure of its gas distribution pipeline. These measures must include an effective leak management program (unless all leaks are repaired when found).

E. Performance measures

PHMSA has proposed that operators develop and monitor performance measures from an established baseline to evaluate the effectiveness of its IM program. An operator must consider the results of its performance monitoring in periodically re-evaluating the threats and risks. These performance measures must include the following:

• Number of hazardous leaks either eliminated or repaired as required by §192.703(c) (or total number of leaks if all leaks are repaired when found), categorized by cause;
• Number of excavation damages;
• Number of excavation tickets (receipt of information by the underground facility operator from the notification center);
• Total number of leaks either eliminated or repaired, categorized by cause;
• Number of hazardous leaks either eliminated or repaired as required by §192.703(c) (or total number of leaks if all leaks are repaired when found), categorized by material; and
• Any additional measures the operator determines are needed to evaluate the effectiveness of the operator’s IM program in controlling each identified threat.

PHMSA has proposed that a new definition for excavation damage be used as a performance measure:

*Excavation Damage* means any impact that result in the need to repair or replace an underground facility due to a weakening, or the partial or complete destruction, of the facility, including, but not limited to, the protective coating, lateral support, cathodic protection or the housing for the line device or facility.

PHMSA indicates that excavation damage is of principal concern and mitigation of this threat means preventing any contact of excavation equipment (or hits) with the pipe. They indicate that the effectiveness of mitigation efforts cannot be evaluated if only hits that result in immediate leaks are considered. Any hit, according to PHMSA, that has occurred (regardless of whether it causes an immediate leak) is an indication that the actions taken to prevent such an occurrence has failed.

**F. IM Documentation**

PHMSA now requires that operators maintain documentation, for a minimum period of 10 years, which demonstrates compliance which demonstrates that the operator has fulfilled each requirement of 192.1007. These records must include copies of superseded integrity management plans.

In accordance with 1007 a plan must have a written procedure for developing knowledge of the network, identifying threats and their consequences (a.k.a. risks) as well as efforts implemented to mitigate these threats. An IM plan needs to also identify a process to monitor and measure the effectiveness of the implemented approach and the production of annual reports to PHMSA.
IV. Review of Infrastructure Management Practices

Many public agencies and utilities have employed varying forms of integrity and infrastructure management systems (IMS) for many years prior to PHMSA new regulations for gas distribution. Industries managing infrastructure that is similar gas distribution, who also have integrity management experience include: state DOTs, water and sewer utilities, and those involved in the transmission of natural gas. Different approaches have been tried and their successes and failures can provide valuable lessons learned for the gas distribution industry.

A. Historical Overview

The history of infrastructure management, originating with bridges, has largely been reactive to failures and for most of the 20th century has focused on moving from a subjective ranking system to a systematic approach based on optimization. Management of bridges and infrastructure had been lead by state governments throughout most of our nation’s history, prior to the 1967 collapse of the Silver Bridge in Point Pleasant, West Virginia. While it is understood that state of art inspection methods at that time could not have found the suspension cable defect that caused the disaster (LeRose, 2001), the Silver Bridge collapse highlighted the lack of continuity among state inspection methods and the inability to take a longer view of bridge management. While the root cause of the collapse of the Silver Bridge was determined to be due to a steel defect and an inadequate design, by 1967 it was also being subjected to enormous loads from modern cars and trucks unforeseen during design in the 1920’s. A national comprehensive review was ordered, finding many additional deficient bridges, and the first national infrastructure management was created known as the Highway Bridge Program (HBP). This program created a national inventory (known as the Highway Bridge Inventory [HBI]) and standardized methods of inspection, design, and management.
The HBP continued to use inspections and rankings of deficiency to determine the level of federal funding and to identify the priority of major rehabilitation or bridge replacement projects. Nevertheless, another round of bridge failures, notably the Mianus River Bridge in Connecticut (1983) and the Schoharie Creek Thruway Bridge in New York (1987), occurred after the establishment of this program. Again, while faulty designs were initially cited, inadequate maintenance, inspection, and management of these structures by Connecticut and the New York State Thruway respectively were identified as the underlying root causes. Specifically speaking about the Schoharie collapse, the American Society of Civil Engineers stated that “the bridge was not re-evaluated using updated knowledge and design philosophies. If it had been, perhaps the sensitive nature . . . . would have been recognized.” (Thornton, 1988).

In the aftermath of these two high profile bridge collapses, which included fatalities and crippled important interstate highways, the Federal government again revised its standards for infrastructure management. As it became apparent that simple ranking methods were not successful in allocating limited maintenance resources among a large population of bridges, the Federal government pushed for the development of bridge management systems which relied on more systematic methodologies. These systems included two components:

1. Deterioration models which could predict the condition of bridge components under the effect of age, traffic loads, and the environment. Deterioration, in the form of scour, was the primary cause of the Schoharie Creek collapse.

2. Optimization models which could use the output of inspections and deterioration models to optimally allocate budgets among different facilities. The Mianus River Bridge had failed in no small part to the inability of an overwhelmed inspection staff to correctly allocate
resources to address priorities. The first successful multi-state implementation of such an optimization model was the FHWA’s Pontis computer software in 1989 (Markow, 2008).

It is important to realize that most IMS have undergone many versions of updates since they were first installed. For example, Pontis began as a DOS version in 1992 but is now a GIS-compatible application with multimedia capabilities and enhanced security features. Improvements in technology will facilitate the other aspects of IMS, such as data collection and storage practices. Hence, when the natural gas distribution industry begins to implement a risk management system, it is important to keep in mind possible future developments. Such developments might include geo-location of newly installed pipelines and their components. Similarly, one can envisage GIS systems becoming a basic requirement for database integration platforms within five to ten years by which time the risk management system implementation would still be underway – and data systems not yet mature.

**B. Transportation Sector**

**i. Pavement Management**

Since 1977, the California Department of Transportation (Caltrans) has been routinely collecting performance related information of its pavement network. However, when their database was investigated in order to develop prediction models for pavement cracking, researchers encountered various issues: (Lea and Harvey, 2004)

- Caltrans was using “dynamic segmentation” to record the pavement information over the years depending on the condition of the surface. To develop predictive models, it is necessary to know the performance of a fixed segment of pavement over time. When the identities of pavement segments change from year to year (as occurs in the “dynamic segmentation” approach) it becomes impossible to track the performance of a given
segment over time. This highlights the importance of using a fixed segmentation for management systems.

- Another challenge that Caltrans encountered resulted from their attempt to tie different pavement databases (maintenance scheduling, pavement condition, design) to one another and then to the physical network information. However, the handling of data was different in each database leading to difficulty in its manipulation – frustrating Caltrans ability to derive useful information from the effort. For example, the milepost information listed within individual records was not consistent across databases, which made cross-referencing information impossible. Caltrans’ experience emphasizes the need to develop an infrastructure risk management system as a stand-alone system, where databases are not used for multiple purposes and hence handled by multiple sets of people.

- Other issues included the age of the databases, wherein the data had been modified over time, with the result that the database contained a large amount of redundant information that was no longer synchronized. After standardizing the data, it was found that the size of the database was reduced by over 30%.

The problems encountered in the Caltrans pavement data highlights the need for infrastructure management systems development to be foresighted and systematic. While Caltrans, with data collected over thirty years, can still work with the reduced size of the database, the high costs associated with inspection and data collection for sub-surface assets like gas pipes requires that the first steps, if properly taken, establish the likelihood of long term success. Specifically, it is important that the network of pipe segments be fixed over time, and that the decision-support risk management system be a stand-alone system. In addition, the size of a segment should be established to be as small as possible. This approach provides the greatest flexibility. If, for example, future regulatory requirements become more stringent (or reporting requirements become more detailed), data assigned to small segments
provides the ability to respond to change (avoiding database reconstruction costs). Block-level segmentation is not likely to provide the flexibility needed to respond to the process of evolution and maturity that will occur over the next decade.

In contrast to the Caltrans effort, there have been successful implementations of pavement IMS in other states such as Arizona. In 1978, the Arizona DOT began work on the development of a statewide pavement management system. The team consisted of management scientists, highway engineers, statisticians, and computer specialists working with the ADOT research staff. The PMS was first applied to the 1980-1981 highway preservation. The PMS process resulted in the substitution of a $32 million preservation program for the $46 million program developed by Pre-PMS methods (in 1983 dollars). The reasons for the savings were the absence of life-cycle cost optimization before implementation. (Way 1983).

Similarly in 1981, the Metropolitan Transportation Commission (MTC) — the metropolitan planning organization for the nine-county San Francisco Bay Area — conducted a study that estimated that spending for local roadway maintenance in the region fell short by $100 million a year, and that the Bay Area's 17,000 miles of streets and roads had a deferred maintenance cost in the range of $300 million to $500 million. In response to this study, MTC started its Pavement Management System in six Bay Area communities as a pilot program in 1984. The full program got under way in 1986. The first version was released in 1987. By 2009 MTC released its ninth version, which is now being used by over 300 organizations nationwide (MTC.ca.gov, 2010).

**ii. Bridge Management**

In contrast to the development of PMS in California, the development of the federal bridge management system, Pontis, was a success and is currently the gold standard for Bridge Management Systems in the United States. The development of Pontis began as part of a FHWA Development Project
in 1989, subsequent to a series of bridge failure incidents, and was first released in 1992 (fhwa.dot.gov, 2010). The developers defined the data requirements through a collaborative process and redefined the way bridge-related inspection data was collected to make it more meaningful for systematic analysis. While there still are institutional and implementation issues associated with its deployment as seen later in this report, these problems can be overcome if the goals of the client agency are very clear as the tools can be customized to its needs. For example, depending on the requirements of the agency, Pontis could act as a stand alone system, or work on data from separately maintained databases. The product was designed in collaboration with six states and was adopted by several states simultaneously, showing that the benefits of a joint effort among the various stakeholders can be significant. This experience highlights the benefits of collaboration across agencies or stakeholders.

Additional successful implementations have been undertaken by individual states such as bridge management systems in both Indiana and North Carolina. However, it is important to note that one of the advantages of implementing IMS for bridge management, as opposed to natural gas distribution, is that the assets are far easier to inspect.

**iii. Bridge IMS Critique post-Minnesota Bridge Tragedy**

One month following the Silver Bridge disaster of 1967, which as previously stated was the catalyst for national standards in bridge inspection, Minnesota opened Bridge #9340 over the Mississippi River in downtown Minneapolis. Forty years later in August 2007, this same bridge, now carrying over 140,000 cars day as part of Interstate 35 (Minnesota DOT, 2006) collapsed during the evening rush hour. Thirteen people died as a result of the sudden catastrophic failure which was attributed to failed steel joint plates due to increased loading on the bridge itself. At the Federal level, many public officials were shocked that the state of bridge infrastructure was so poor that a bridge in the Interstate system could fail, and called for a general review of procedures including the allocation of funds to fixing bridges,
known as the Highway Bridge Program (HBP), and how the states utilize infrastructure management to use said funds. Congress called on the General Accounting Office (GAO) to review the HBP and produce a report.

iv. GAO Report on the Effectiveness of the HBP and IMS

The GAO’s report was highly critical of the HBP, and much of the blame was directed toward infrastructure management at the state level and the lack of oversight of IMS at the Federal level. Their conclusion was that “The HBP does not fully align with principles established in our previous work . . . . the program lacks goals that are focused on a clearly identified federal or national interest, performance measures, and sustainability” (GAO, 2008). More specifically, the GAO was concerned that funds were being allocated based upon one criteria (percentage of bridges with problems as defined by Federal guidelines); while states were using the funds for different purposes (as they were permitted). This is where IMS came into view. The GAO visited six different states, and although all six had implemented bridge management software (such as Pontis), only one, Missouri, had an explicit scoring system available to the public that took into account other factors such as economics and social benefits. The GAO concluded the HBP was giving, and continues to give, funds that are not accountable to Federal oversight due to each state’s individual method for managing their infrastructure. They cite improving IMS software as an effective way for achieving this goal.

The GAO conclusions have a high degree of relevance to the natural gas industry. It is not effective to simply to employ computer-based IMS systems if the results of the software are not tied to funding and repair mechanisms in a clear-cut way. Coordination between inspection teams, IMS computer specialists, and management is required for any success in infrastructure management. A plan of action which utilizes IMS must come from the executive level.
v. Maine’s infrastructure management response

The reaction to the Minnesota collapse among the individual states was more varied; most states took a serious look at any bridge with the same design as Minnesota Bridge #9340 and then continued with the status quo. With gridlock at the Federal level (as documented in the GAO report) there was no specific push for change. However, an exception to this rule was the State of Maine, which took a proactive approach and undertook an overhaul of their bridge infrastructure management practices.

The average age of Maine’s bridges is very similar the infrastructure of natural gas, with many older structures exceeding 90 years. The state’s comprehensive review, a process which can be applied to all types of infrastructure is outlined in Maine DOT’s document “Keeping our Bridge’s Safe,” published in 2007. The review consisted of the following steps:

1) Identify the Safety Risks – What are the conditions that cause bridge deterioration or failure? Within Maine, how do we rank these risks?

2) Review of the State Inspection Program – Is Maine complying with Federal requirements on bridge inspection? Is there room for improvement?

3) Consider Enforcement – Are overweight trucks overloading older structures? Are contractors using best practices when working on or near the bridges to prevent damage?

   How can Maine improve enforcement?

4) Question Technical Competence – Are inspectors, both in the private and public sector, trained to identify sources of concern?

5) Examine Management of Inventory – What are the guidelines for replacement, rehabilitation, and upkeep of Maine’s bridges, in particular those over 80 years old?

This review identified a number of concerns, which were narrowed down to twenty-five specific recommendations in the categories of inspection, maintenance, and capital investment. Maine’s
exercise was highly successful and resulted in a massive increase in funding from the state legislature as well as an increase in public confidence in Maine DOT.

One could see how Maine’s review questions can be applied to natural gas infrastructure management, and many of the questions have already been answered. What are the primary risks to natural gas distribution lines? Can the industry have a better relationship with contractors to improve damage by third parties, perhaps through better enforcement of best practices? Can the natural gas industry develop a more automatic plan for replacement of known older pieces of infrastructure based on probabilities of failure?

**vi. Conclusions from the Transportation Sector**

It can be seen from the experiences of the different stakeholders within transportation, that the development of a transportation IMS may take anywhere between 3 and 6 years. However, this timeframe is not a true reflection of the work that lies ahead of the natural gas industry, given the uncertainties associated with the available data and high inspection costs for sub-surface assets, which complicates the task of inspection and data collection.

The experience in the transportation sector with risk management practices has been promising, if not always successful. While some of the practices may not be transferable to the pipeline industry, the basic principles are likely to remain the same. The long timeframes associated with development and implementation observed in the transportation sector, reveal that the evolution of a risk management system for the natural gas industry, will be a slow process. In addition to being slow, it has been observed from the past experiences that IMS development is a process seeking continuous improvement. The improvements would continue to happen in database development, on the technological front and in the better integration of IMS into the decision-making set-up, all of which would likely extend over a decade, or more. Ultimately, the successful implementation of IM leads
toward a change in business processes, an increase in the investment in new technologies, as well as a change in how decisions are made.

**C. Water and Sewer Experience**

Other fields, sharing some physical similarities with the natural gas industry, have had similar management efforts with varying degrees of success. These include the transport of water and wastewater (sewer) through underground pipelines. In many circumstances, many of the concerns and questions being raised by the natural gas industry have already been raised in these two other fields. Infrastructure management has been slow in both water and sewer due to a number of obstacles. Roger Smith from the Texas Transportation Institute has cited institutional problems, such as the resistance to change at the organizational and individual level, as a primary source of difficulty (Smith, 2004). Others cite financial concerns as a primary obstacle to the adoption of infrastructure management. The sewer industry specifically has been very emphatic about the funding crisis; it has been stated that sewer management in the United States consists of “clean the inlets as you can afford and fix the system when in fails” (Fenner, 2000). The federal agency has added an additional concern; the sheer size of the infrastructure and the different failure modes for all of the various materials (EPA, 2007). Given this size, the EPA has suggested caution on creating a one size fits all IMS system, the only exception being the examination of faults on joints and connections, a failure that occurs with all materials and ages of pipes.

All parties however are in agreement that the larger pieces of infrastructure, such as sewer and water mains, can be inspected fairly easily with existing technology, which in turn could lead to the effective implementation of IMS in the United States. One well-established technology is that of CCTV, which can negotiate water and sewer mains and take very detailed pictures. Nevertheless, an obstacle remains in the engineer’s ability to interpret the pictures taken by the camera, and CCTV cannot detect
problems outside of the inner wall of the pipe. Due to these constraints the EPA, in their 2007 report, admitted that “condition assessment . . . is not likely to produce a precisely accurate prediction of failure.”

Much like the natural gas industry, both the water and sewer fields have difficulty addressing the distribution network and pipes under pressure known as force mains. These smaller pipes, known as “private lines” or laterals, connect to and from municipal mains. The EPA reported that a majority of infiltration of groundwater into sewers occurs in laterals, and that damage by tree roots typically occurs in these distribution pipes as well. For force mains, in both the water and wastewater industry it can be difficult to turn off and bypass service, leaving the utilities the task of examining the force mains while it is in service under pressure. It is particularly difficult to install permanent sensing equipment in force mains while they are in operation.

i. Federal Efforts to Address Risk Management in Water & Sewer

Throughout the first decade of the 21st century, it became clear to the EPA that the severe funding gap, in both research and implementation, was becoming a detriment to the well being of the operation of the water-sewer infrastructure. By 2005 the U.S. Geological Survey had estimated that over 1.7 trillion gallons of water per year were being lost by the nation’s water infrastructure at a cost of 2.6 billion dollars (EPA, 2007). To combat this crisis, the EPA’s research arm created the Aging Water Infrastructure Research Program (AWI), whose top priority was to promote better management of the current water utilities through “conditions assessment” and “system rehabilitation.” In this vein these objectives are remarkably similar to the initiatives being explored by the natural gas industry. The research initiative has already seen success in creating a comprehensive review of the state of technology for both water and sewer, as well as producing core questions that will govern future research funded by both public and private sources. The questions “reflect critical gaps in our
knowledge,” according to the EPA, as well as strategic challenges (similar to those posed by DIMP legislation):

1. (Water) Can innovative technologies and procedures substantially improve condition based management of drinking water infrastructure assets?
2. (Sewer) Can guidance be provided for establishing a comprehensive system rehabilitation program, including rehabilitation of non-sewer assets?

**ii. European Efforts to Address Risk Management in Water & Sewer**

European Nations, with utility infrastructure even older than the United States, have also been serious with asset management in the water and sewer fields. Multiple nations, including Belgium and the UK, have employed an alternate model since the 1990’s which has been successful: looking at the economic consequences of failure and working backward toward inspection, maintenance, and replacement. For example, in Belgium individual sewer districts identified pipes that were “strategic” based on the financial and ecological consequences of failure (Cobbaert et al., 1998). These pipes were given proactive maintenance and subsequent replacement if necessary; while other non-strategic infrastructure was relegated to the traditional “fix the problem when it occurs” status. This enabled the country to apply limited resources with the largest benefit.

This alternate approach found by Cobbaert in Europe for water and wastewater management has a strong relationship to the direction that the natural gas industry might pursue for the management of their distribution lines. Risk management, in terms of looking at consequences, has already been shown to be effective in transmission lines, gas pipes whose failure would create the highest level of negative economic consequences.
Identifying crucial distribution lines in terms of economic terms, such as those for large commercial centers, a school, or hospitals, is a worthwhile endeavor, as shown in the European experience with water and wastewater.

**iii. Conclusions from Water and Sewer Sector**

In most instances, water and sewer lag behind bridge and pavement in the progress they have made in their migration from a reactive to a proactive asset management approach. However, many of the new concepts developed by the water and sewer industry do have relevance as they concentrate on pipeline management, which to some degree is more applicable than bridge management IMS. In particular, the emphasis on quantifying the consequences, hesitancy to use condition assessment alone, and the importance of filling knowledge gaps should be priorities for the natural gas distribution industry.

**iv. Current State of the Practice**

At one of the most recent conferences of the Australian Road Research Board (ARRB), there were a number of papers on the topic of IMS. Anthony Kane (of AASHTO, a US association of Highway officials) and Stephen Gaj of US Federal Highway Administration (FHWA) presented on trends in roadway asset management, and did not speak highly of the ability to quantify success at the Federal level. Fifteen years after US federal legislation (ISTEA) first mandated IMS (although that mandate has been repealed); Kane reported that the primary focus of AASHTO is still to assist states with implementation, rather than to quantifiably critique the implementation. The number one research gap cited by the authors was the “tie-in of asset management [IMS] and performance metrics as part of comprehensive state processes,” meaning that the connecting IMS to other state management systems was still an ongoing effort. Furthermore, in their domestic review of state agencies, they noted that “agencies vary in their definition, applications, and tracking of preservation actions” and that asset management still stood
apart from new construction of additional capacity. Most importantly, risk analysis was a very low priority:

“There was very little evidence of the application of comprehensive risk analysis in the asset management process observed. The most common risk considered during programming and budgeting is the risk of project cost overruns.”

Kane and Gaj concluded that the “priority for FHWA . . . is to focus on performance measures that tie back to the goals of the respective agencies.” In terms of successful roadway asset management through IMS, it appears that the United States still has some significant obstacles to overcome. Similarly, Bob Peters, presenting for the World Road Association, echoed the remarks of Kane and Gaj in his paper at the same conference. He stated that the “difficulty in advancing risk sharing life-cycle costing, and other techniques rests in budgetary shortfalls.”

v. U.S. Federal Government Involvement

The FHWA has vast resources available online for all types of transportation infrastructure, including instruction on setting up asset management as well as reports from many different states. More importantly, it has published case studies from many different states, including those using the federal software programs for cost-benefit analyses such as HERS-ST (Highway Economics Requirements System/State Version).

However, despite the overwhelming amount of information available at FHWA, it appears that the transition from promoting implementation of IMS to monitoring and quantifying the success of IMS is progressing slowly. For example, although there are case studies for varying types of infrastructure management from 20 different states in some form, these documents focus on lessons learned from
each individual experience. The FHWA it appears has not issued any omnibus documents which agglomerate all of the experiences, but rather continues to keep the individual focus areas separate.

The lack of overall performance metrics from FHWA and other Federal agencies for infrastructure management has caught the notice of the government’s in-house investigatory arm, the General Accounting Office (GAO). As stated and discussed previously, the catalyst for this effort was the collapse of Minnesota Bridge #9340 in August 2007, which caused the death of thirteen people. The GAO issued two important reports, one specifically targeting the Highway Bridge Program (where IMS is specifically discussed as a critical tool), and one with a more broad examination of the nation’s infrastructure. This second document, titled “Surface Transportation: Restructured Federal Approach Needed for More Focused, Performance-Based, and Sustainable Programs,” lists four major recommendations. Most notably, these recommendations include “a need to improve the use of analytical tools in the selection and evaluation of the performance of projects.” Asset management utilizing IMS software remains the most effective way to implement these recommendations by quantifying projects.

**vi. International Evaluation**

Over the past decade, the World Bank has also been funding IMS, specifically road management systems (RMS), with a broad range of results. While the World Bank has not fully quantified measures of effectiveness, it does have a formal set of technological requirements that it seeks to achieve across all projects, and offers recommendations to achieve these goals. These requirements are outlined in the report “Success Factors for Road Infrastructure Systems.”

Overall, the World Bank focuses on four major headings – adequate funding, effective implementation processes, support for the project at the upper levels of management, and the appropriate use of technology. The latter three are explored in depth with many specifics in the
conclusions section of “Success Factors.” Not surprisingly the World Bank notes that there is typically too much emphasis on technology, and not enough on human support. In fact, without full institutionalization of the implementing agency for IMS, the World Bank concludes that the project will fail. They found that using consultants for the bulk of the project, followed by shallow “on-the-job” training and presentations to upper management “completely inadequate.” This is a common problem in the implementation of IMS in the United States.

**vii. Current State of Practice Conclusions**

Different agencies offer different levels of support for the implementation of IMS, and subsequently have different ways (or none at all) to measure the effectiveness of these systems once they are operational. For example, FHWA has a tremendous amount of support resources available online, but have yet to venture into the discussion on which IMS implementations they favor and why. The World Bank appears to be ahead of FHWA on this process, although more research will need to be conducted to review the state of affairs in Europe and Australia. However, as noted at the ARRB conference, across the globe IMS implementation remains a work in progress.
V. Survey of Data

As illustrated through the experience of other industries, in their application of infrastructure management systems, success is highly dependent upon appropriately matching modeling and data processing approaches with the type, extent and availability (in a digital format) of information about the infrastructure.

Many long-life infrastructure networks share the same challenges in the application of computer-based systems to their management, typically:

- Data is limited in the extent to which it describes the infrastructure, such that there are aspects of the network that have not been chronicled
- With regard to network characteristics that are monitored, the quantity data of the available is limited. Data quantity limitation results in a higher level of uncertainty.
- The data is distributed throughout the organization and it is not explicitly associated with a relevant segment
- There is a high level of uncertainty associated with historic data.

A survey was conducted to determine the nature of data today and which, if any, of the anticipated challenges are likely to be encountered. The survey began with an examination of the records that are retained upon the initial construction and then examined records of operational data.

A. Asset Records

One of the findings of the survey is the long-term trend for the migration of data management systems toward digital platforms. This provides a high degree of flexibility, but requires the consolidation of records previously maintained in a distributed fashion and frequently only in hardcopy (written form, paper-based). This data migration effort is underway but largely not complete.
Comments provided by project sponsors indicated that challenges for the adoption of a digital platform and the attendant data migration grows in complexity as the organization grows in size. This complexity is a natural consequence of the increase in the quantity of and variation in existing distributed data management approaches, large networks of operations and engineering stakeholders and a plethora competing demands on the information systems department.

Asset information can be quite comprehensive, including pipe type, diameter, material, length, year of installation, operating pressure, location and the existence of cathodic protection. Faith in the accuracy of the information is greatest for recent information, but declines with age.

This is because most gas distribution companies, today, were assembled through the consolidation of many smaller companies. Predecessor organizations operated in different environments – with data management philosophies appropriate for that time. Many of these historic records, however, do not meet today’s standards and they require significant effort to be utilized in an information management system. Today asset records migration efforts are largely a work-in-progress; consequently digital records cannot commonly be utilized to facilitate automated analysis.

Survey Question: Upon completion of a new facility, today, what information is retained?

1. An electronic image file of field notes is stored in ESRI.
2. Field notes, as built drawings and CPR
3. A continuing property record, gas maps for field use, and as built print file for the original job.
5. Currently a hybrid raster/vector AM/FM Mapping System. We are in the process of implementing a GIS. Limited facility information for financial reporting and rates is maintained in Peoplesoft Assets by age group but not pipe segment.
6. Very descriptive. Our maps include [extensive descriptive characteristics] and a unique segment id for the pipe ...
7. My company utilizes an electronic Geospatial Information System (GIS) as our asset record.
Asset records can provide many descriptive details of the asset but historic data infrequently provides details on the environment in which the asset is located (in some cases, more recent data is different). This has important implications for the implementation of infrastructure and risk management systems, as operational data will be the only possible source for environmental data.
Would any of the following information about the general environment where the pipe is installed be available with asset records?

- Area Type (such as urban)
- Traffic (such as high, low)
- Is the pipeline installed in a region that is a designated Trunk Route?
- Road Type (Pavement type: Soundless, gravel, asphalt, etc.)
- What is the likelihood that historic information is complete and of r...

Is detailed information available in historic records about structures that are associated with a particular pipe segment?

- Continuous Paving from building to building
- Does structure have basement?
- What is the likelihood that historic information is complete and of r...
B. Maintenance Records

The transactions of operations are documented and maintained in a variety of record management systems. Historically, maintenance records were recorded on maps that were maintained by the responsible regional operating division (for leak repair, for example) or discipline-specific operating department (for cathodic protection, for example). Although paper-based record keeping persists (with 28% of respondents indicating that only paper-based record management techniques are in use) most companies utilize some form of a database management system and have historic data of maintenance actions that extent over the last 10 years (as a minimum).

In most cases each maintenance action is uniquely identified by address, but they may have other unique identifiers (such as being directly associated with a pipe segment or work order).
In addition to asset characteristics, maintenance records also provide descriptive information on the cause, action taken and outcome of the maintenance task. Finally, maintenance records contain high quality information.

Maintenance records, generally, do not include information about the environment in which the pipe is installed, with the exception of noting the type of environment (residential/urban) and the location of the pipe in the right-of-way (such as center of the street).
Would any of the following information about the general environment where the pipe is installed be available with maintenance records?

Would any of the following detailed information be available in historic maintenance records?
C. Other Sources of Information

i. Corrosion Survey

Steel piping installed after 1972 is electrically protected to inhibit corrosion, this is also true for some percentage of steel piping installed prior to 1972. The operational status of corrosion protection systems (which can include pipeline coating and an impressed current) are periodically determined through measurements taken at the site of the pipeline, in accordance with regulations. Historically information that results from a corrosion survey, as they are known, would be retained the surveying department. There is a trend for this information to be more widely accessible to the organization:

- 28% of respondents indicated that corrosion survey information is currently available for use in engineering analysis.
- 43% of respondents indicated that corrosion data will be available as the information systems evolve, as planned
- 28% of respondents indicate that corrosion data is maintained on separate system and is not easily accessible for engineering analysis

ii. Inspection

Exposed gas distribution pipelines are commonly inspected and an inspection record is created. The creation of these records is prompted by excavation activities and are incidental to the work being performed. The inspection is one of several activities associated with the excavation, and because of that association information such as pipe size, operating pressure classification and location are captured. Other detailed information – such as information about the location or pipe environment – is not generally collected.
iii. One Call

Excavation tickets, issued by a ‘one-call-center’ represent another potential source of information about threats to an individual segment of pipeline. Respondents to the survey indicated that this information is largely available, although in some cases it may require effort to put in useable form.

This information is generally not maintained in-house but is made available by the one-call vendor.

iv. Construction Coordination

The public right-of-way is crowded with facilities owned and operated by other privately owned and municipally owned utilities. These assets undergo their own deterioration processes and require maintenance and eventual replacement. This third party construction presents a threat to existing gas mains that can be appropriately ameliorated – if proper prior notification of the third party is available.
One survey question examined the notification of third party construction, and did this notification timing allow the company to appropriately protect their facility.

- 14% of respondents indicated that they do not receive prior notification from either municipal or a privately owned utility.
- 57% of respondents indicated that adequate notification is available from municipal utilities – but that privately owned utilities do not provide advanced notification.
- 28% of respondents indicated that advanced notification is provided by BOTH municipal and private utilities about their pending projects.

A second survey question examined municipal efforts to notify utilities of pending street pavement rehabilitation projects. All of the survey respondents indicated that they receive notification of pending pavement projects; 71% indicated that the notification provides adequate time to evaluate the need for and execute a gas pipeline replacement project, 29%, however, indicated that notification timing is inadequate to execute a replacement – when needed.
VI. Conceptual Development of a Risk Management Approach

A. Overview of Risk Management Practices

The discussion on the past and existing infrastructure management practices in the previous chapter briefly describes the evolution of risk management approaches from ranking-based techniques to optimization procedures. However, before deciding upon a particular risk-mitigating strategy, it is important to understand the strengths and limitations of different methodologies, so that a company can effectively choose between different solution methods.

Optimization vs. Ranking

Optimization refers to solving problems in which one seeks to minimize or maximize an objective value (cost, number of incidents, etc.) by systematically selecting the appropriate decision variables (projects for replacement, different replacement options, etc.) from within an allowed set of options (based on the various financial and resource constraints of each company). A ranking procedure involves evaluating all possible solutions on the basis of a single criterion (or multiple criteria jointly assessed using predefined weights) and using it to generate an ordered list of solutions.

While both approaches seek to determine the best available solution (or an "optimal" solution), they differ in several ways (mentioned below) which lead to optimization becoming a superior method than ranking:

- Complete enumeration (ranking) vs. "Smart" selection (optimization): Ranking requires all projects to be evaluated in order to find the best solution whereas optimization, being based on proven mathematical concepts, intelligently navigates through the solution set to deliver an optimal solution. Clearly, explicitly eliciting all possibilities is cumbersome and unreasonable for large problems.
• Performance under uncertainty: One of the major drawbacks of ranking methodologies is in their underlying assumption that there is no uncertainty in the data. That is to say, ranking systems require completely accurate data. Real world infrastructure management, however, is based on data that are influenced by multiple sources of uncertainty. For example, if the data were directly measured it is subject to sampling and measurement uncertainty (which means that multiple measurements from randomly selected sites are required to reduce variation and in turn, produce data with a high level of confidence). Under some circumstances, older historic data are used. Such data could be inaccurate, because the very passage of time introduces the natural forces of change upon the environment and the condition of the asset. Another source of uncertainty in data is when it must be intelligently estimated by operators – because no real data exists. The very nature of data used in infrastructure management causes ranking methodologies to produce inaccurate results. Optimization, in contrast to ranking, directly addresses data uncertainties by associating probability distributions with data. These distributions describe the natural variation that is associated with all real world data. Risk, in the context of distribution pipeline integrity management incorporates uncertainty in its very definition (as risk has been defined as likelihood [or probability] of occurrence of some incident multiplied by the [estimated] consequences of that incident). Risk management that utilizes data that incorporate any uncertainty is best addressed by optimization-based methodologies.

• Subjectivity vs. transparency: ranking systems are also recognized as being strongly influenced by the interpretations of individuals participating in asset assessment - because they use ad hoc weights, which can vary from individual to individual and even over time by the same individual. An optimization-based solution is devoid of subjective inputs and is therefore seen to be more objective and transparent.

Experiences from other industries indicate that their journeys in risk management began by using ranking methodologies. However, the limitations of the approach were soon discovered (inaccurate budgeting, poorly assessed risks and improper quantification of priorities), which eventually led to these industries adopting optimization tools to assess risks and identify priorities. In many cases, this transformation was brought upon through extensive collaboration of the industries with the federal government, as demonstrated by the development of the bridge management system (BMS), Pontis.

**Top-down vs. Bottom-up Approaches**

Top-down and bottom-up are strategies of information processing and knowledge ordering, and are used to break down the decision-making process into stages. In the top-down approach, aggregate maintenance and replacement decisions are made first at the system level, then translated into
decisions for individual facilities (pipe segments); in the bottom-up approach, decisions are made at the facility-level first and then aggregated to the system-level.

**Top-Down Approach**

In a top-down approach, an overview of the system (i.e. the pipeline network) is first formulated by specifying, but not completely detailing the base elements, i.e. the pipes, valves, joints, etc. After solving the maintenance and replacement problem at the system level, the solution is broken down to the subsystem level (ex. “Asset Family Classes”\(^1\)) in order to achieve greater granularity and accuracy through the specific information pertaining to the individual segments. A top-down model is often specified with the assistance of simplifications about the elementary mechanisms (of pipe failure, third-party damages) which make it easier to manipulate and simplify the computations needed to solve for the optimal solution. However, the required simplifications need to be made carefully so as to remain consistent with the realism of the problem. For example, to assume that all pipes deteriorate in the same fashion would be very simplistic, but very inaccurate; however, assuming that all old steel pipes without cathodic-protection installed in a downtown area have similar age-related deterioration, which is different from cast iron or plastic pipes, would be reasonable.

**Bottom-Up Approach**

In a bottom-up approach, the base elements of the network i.e. the pipes, valves, joints, etc. are first specified in great detail (and assembled into a large database). The problem of maintenance and replacement decision-making is first made for each element individually based on a life-cycle optimization formulation. In the following step, these elements are then linked together to form larger subsystems (blocks, neighborhoods, asset classes, etc.) which in turn are linked together, until the network is formed. At each step, the decisions made at the earlier level may be modified to account for

\(^1\) “Asset Family Classes” will be defined in the section on the Proposed Methodology
system-level constraints (e.g., budget constraints). This formulation provides a more accurate representation of the network’s deterioration, but is significantly more complex to solve and is heavily reliant on information being available on all elements (and their surrounding environment) to effectively model their wear and tear (with engineering models) and describe their economic consequences.

**Motivation for Top-Down Approach**

Based on the description of the two strategies and given the current limitations of data availability, it can be inferred that it is unrealistic and infeasible to begin with a bottom-up approach. Another important factor benefiting a top-down approach, especially for the initial stages of DIMP implementation, is the use of expert opinion. In the absence of substantial data, the knowledge of experts is often used to contribute to the initial estimates of information about the network (as shall be explained in subsequent sections). However, such type of information is more relevant for top-down approaches wherein such simplifications are in fact sought after. In a bottom-up approach where precision of the segment-level information is the key, approximate information is not very useful and can defeat the very strength of the approach.

**Note:** While making the argument for a top-down approach, it is also emphasized that the quality and quantity of segment-level information should be continuously improved, thus improving the quality of the decisions made in later stages of the development and application of the risk-management system. This improvement also allows for making better simplifications while defining the Asset Family Classes.

**B. Proposed Methodology**

The top-down optimization approach combines assets that have similar characteristics, threats and behaviors into Asset Family Classes and utilizes recognized mathematical algorithms to defensibly allocate resources and establish priorities for action among these classes. Risks to pipeline segments and
their consequences would be defined within each Asset Family Class by company experts, during the top-down optimization implementation process. As such, the definition of an asset family reflects the situation that an individual company faces – both in terms of the physical environment as well as the information that is available to define the class. The optimization algorithm would be applied to the classes on an annual basis, or any other planning cycle, to minimize total risks and costs. The role of optimization is to allocate resources (budget, etc.) across the classes and establish priorities to each class, in a manner that is both robust and defensible.

The predefined Asset Family Classes would then be used by operations and engineering staff to classify new projects and pipeline segments, as they are continuously encountered throughout the year. This classification would assign a set of priorities and options to these segments, in relation to other opportunities and challenges that the company encounters on a continuous basis.

This results in a two-step process, wherein the first step involves optimization procedures, whose results are then used by the engineering staff to select projects within each class.

**i. Defining Asset Family Classes**

In the proposed methodology for risk assessment, the approach uses top-down optimization with the help of company-defined Asset Family Classes. The advantage of using such an approach is that the top-down optimization results in allocating a budget to all classes on the basis of risk minimization, which can then be used to conduct replacements/ maintenance of pipes within each class. The analysis implicitly compares the risks of all the classes with each other.

The role of Asset Family Classes is to minimize the data requirements for the decision-making process while making use of Subject Matter Experts (SMEs) to fill in the knowledge gap. But at the same
time, the class definition needs to facilitate risk assessment. Hence, the basic attributes of an asset class
definition should include:

- Characteristics of the Class Component (e.g., material, diameter, construction, pressure of pipes, maintenance history)
- Threats (e.g., frequency of third-party construction)
- Environment (e.g., zoning)

**ii. Defining Risk Using Asset Family Classes**

![Figure 1 Schematic Diagram for Risk Assessment in an Asset Family Class](image)

As can be observed from the schematic diagram in Figure 1, in order to effectively define risk, the probability of a leak and the costs associated with a leak leading to an incident need to be ascertained. The probability estimate will depend on the characteristics of the class components along with the threats associated with each class, since it is the combination (for example) of the frequency of third-party construction along with the response of the pipe to such activity (driven by its characteristics) which informs the estimation process. Similarly, age-related deterioration is also encapsulated by the characteristics of the pipes belonging to the class.
To quantify risk, it is also essential to know the environment to effectively evaluate the costs (of consequences) and the conditional probability of an incident given a leak has occurred, as the progression of the leak into its surroundings and the associated consequences depend on the environment in which the pipe is situated.

The representation of asset family classes based on the three attributes discussed above allows for a simplified decomposition of risk, which is also consistent with the PHMSA regulation as it incorporates the threats from third-party activity, which is an integral part of the regulation. However, the data used to define these attributes can vary from company to company. Hence, using little data to represent the attributes of a class will lead to the creation of a smaller number of classes, whereas the use of more attributes and detailed information increases the number of classes defined, as well their granularity.

### iii. Expert Elicitation

Expert elicitation involves directly consulting company, industry or subject matter experts (SME) through a structured survey of their insight. One of the benefits of expert elicitation is that experts are generally able to provide knowledge on attributes that are variable in nature, and help define which attributes among the three categories are well covered and which require more research. In an effort to obtain precise data, questions should not ask for amorphous values such as probabilities or likelihoods, but rather tangible units such as time, dollars, or yes/no answers. This is illustrated below.

### iv. Data Requirements of a Class

Data requirements for a class of assets in top-down optimization are different from bottom-up and ranking approaches. PHMSA regulations indicate that unique characteristics of a segment, its environment and threats to its integrity should form the basis of decision that fosters actions and investments that mitigate risks. Data requirements have been discussed at length in the Gas Piping Technology Committee (GPTC) and elsewhere. Their general conclusions are that the availability of
detailed attributes of the gas main and its environment can either be used to rank (if uncertainty in information is very low) or used in conjunction with scientific, engineering or statistical relationships (that quantifies cause and effect) to calculate risks and resultant priorities on every individual segment (this would be typical of a ‘bottom up’ optimization approach).

The top-down optimization approach, in contrast, allows for the definition of a class on a limited set of data, as well as the utilization of expert opinion, estimates of and surrogates for data. Further, as optimization establishes priorities, segments assigned to classes that have a low assessment of risk (and low priorities) will likely require no or limited additional data and analysis. Conversely, for a segment that is recognized as belonging to a high priority class (based upon risk), a company would be justified to collect additional information (such as assembling maintenance histories, or perhaps perform a leak survey) to establish that an appropriate risk mitigation action is taken.

To illustrate the flexibility that the top-down approach offers and to identify specifics that might be needed for a class, consider an example class described in the following section.

v. Example Asset Family Class

Subject matter experts might define an Asset Family Class with the following five criteria. These criteria would be used to screen segments and to assign these segments to the class.

- Cast Iron Pipe, 4 inch in diameter and below,
- Operating at low pressure,
- That has previously experienced a break,
- Previous breaks or leaks have been classified as Leak Classification 1 / 1a, and
- This segment is located in an area of frequent construction (repair and replacement) on utilities owned by third parties.

The class definition is consistent with the asset class definition defined previously as follows:
• **Characteristics of Class Component**: GPTC discussion suggests that segment location, operating pressure, material & age would need to be known. In our case we have defined pipe diameter, operating pressure and material as important attributes to define this class. In the case of cast iron, age is not strongly correlated with segment deterioration and risk, so it has not been included in our class definition either. The knowledge of historical records of maintenance also contains important information to gauge the behavior of the pipe segments. (For the top-down approach, location information is associated with an actual segment and not a class and thus, it is not included in the class definition.)

• **Environment**: GPTC suggest that detailed information should be assembled about the environment in which a segment resides (which implies information that characterizes the soil, the pavement extent, the distance to and density of buildings). Such information, if available, would be useful when used in conjunction with causative relationships that defines risks based upon environmental attributes (as would be done in a bottom-up optimization approach). However, in defining the Asset Family Class example for top-down optimization, we will use previous leak classification information as a determinant of risk. Leak classification is a surrogate for the segment environment – and it effectively quantifies how gas migrates towards structures for that particular segment – thus defining behaviors that create risks.

• **Threat**: Incorporating the threats to segments within the class is an integral component for quantifying risk and also consistent with the PHMSA regulation. In the case of the above-defined Asset Family Class, the presence of frequent construction activity in the area is the primary threat.

**Risk Assessment**

Risk Assessment includes three steps: first, given the Asset Family Class characteristics, a Threat analysis is conducted and the probability of a leak, \( P(\text{leak}) \), is obtained. Next, the probability of an incident, \( P(\text{incident}) \) is computed by multiplying \( P(\text{leak}) \) by \( P(\text{incident}|\text{leak}) \), which is the conditional probability of an incident given a leak has occurred. Finally, Risk is obtained as the product of \( P(\text{incident}) \) and the Cost of incident (which includes direct costs and the loss of goodwill).

Threats and their impacts will be quantified through the assembly of data, when available, as well as expert opinions collected from appropriate company staff (engineering, operations and management). These opinions are collected through a structured survey (expert elicitation), which quantifies the uncertain nature of an asset’s behavior to a threat. Top-down optimization utilizes this quantification of uncertainty in its optimization algorithm, to produce a “robust” allocation of resources and establish priorities for future data-collection. The ability to produce recommendations that are not sensitive to
small changes in data and parameters is a characteristic strength of optimization (and a characteristic weakness of the ‘ranking’ approach).

Robust recommendations are particularly important in distribution pipeline risk management because less data are available and a greater level of uncertainty is associated with all the data that are available (as a result of sampling and measurement errors) than any other infrastructure management.

Step 1: Threat analysis

PHMSA regulations require that a variety of threats to a segment be considered, including:

1. Corrosion
2. Natural forces
3. Excavation Damage
4. Weld, joint or coupling failure
5. Equipment failure
6. Incorrect operations and
7. Other concerns that could threaten the integrity of the pipeline.

The team of Subject Matter Experts (SME) would consider each threat individually, utilizing both data and expert elicitation to characterize the impacts of the threats on the specific asset class. The SME would develop a consensus vision of the nature of the threat and then characterize asset behavior to the threat by responding to a series of questions. This exercise will quantify the probability of a leak for the asset class under the relevant threat.

Sample questions illustrating the role of SME in quantifying threats are shown in APPENDIX A.

B. Computing the probability of an incident

The following example will illustrate how to compute the probability of an incident. The SME have already quantified the probability of a leak, which is the probability that the physical integrity of the pipeline will deteriorate and create conditions that will allow gas to escape from the main – and migrate
within close proximity of an enclosed space (a building). For an incident to occur, this migrated gas must find a means to enter a building and then encounter some source of ignition while the concentration of gas is within its range of flammability. The SME estimated this conditional probability of an incident as the ratio of number incidents (over the past 10 years) to the number of type 1/1a leaks over the same period in time. Multiplying P(\text{leak}) by P(\text{incident} \mid \text{leak}) will produce the desired probability: P(\text{incident}).

C. Risk computation

There are several costs that are used in the proposed optimization procedure, including:

- Consequence costs would generally be estimated once and would be applied to each class, as is appropriate to class definition.
- Maintenance cost: The cost of emergency maintenance will be estimated from company statistics for the costs of Type 1/1a leaks that require more extensive resurfacing – characteristic of ‘protected streets’.
- Replacement costs: The optimization algorithm compares the option of maintaining the existing pipeline assets (along with the likely consequences of the risks) to the replacement option. Thus replacement costs need to be estimated. For this class the SME estimated that a typical pipeline segment would be 500 foot in length and would include tie-ins (2), service replacements (estimate 15), saw cut, excavation, pipe installation (like size), backfill, compaction, temporary pavement and typical traffic control. Note that this estimate does not include permanent pavement in the restoration costs as a municipal pavement program is assumed.
- Direct costs of an incident: The direct cost of an incident will be estimated by the company’s management.
- Loss of Good Will: The Company’s management will also provide an estimate for the intangible costs associated construction in protected streets and incidents.

The last two cost components are those that are relevant to the computation of risk. By definition, risk is the product of P(\text{incident}) and the cost of an incident, which includes the direct cost and the loss of goodwill associated with the occurrence of an incident.
vi. Summary of Proposed Methodology

The proposed methodology for the risk management system can be summarized as a two-step top-down approach.

I. The first step involves the simultaneous optimization of the entire network (consisting of the different Asset Family Classes) to determine what fraction of pipes within each class need to be replaced or maintained. In effect, it allocates a budget to each class for pipe replacement and maintenance, which is used as an input (along with the percentage of the pipe network needed to be replaced), for project selection within each class. The first step requires the following inputs:

- List of actions for replacement and maintenance and their respective costs (in $/unit mile of pipe replaced/maintained): 
  - Do-nothing (base case scenario)
  - Replacement by plastic pipe, steel pipe with cathodic protection, etc.
  - Maintenance activities for existing pipelines (such as leak repair for cast iron and steel or cathodic protection of steel pipes)
- Company-defined classes and the associated parameters:
  - Miles of pipe within each class
  - Transition probabilities for each class and action combination: defining the probability of a pipe of unit length to undergo an incident in the following year, given that a particular action is carried out in the given year
    - The transition probabilities is the product of two probabilities:
      - Probability that a leak occurs in a given class (function of segment attributes, segment history, threats within a given class, and the action carried out)
      - Conditional probability that an incident occurs, given that a leak has already occurred (function of segment environment)
  - Costs of different actions
- The Capital and Operations & Maintenance (O&M) Budget for the current year
- Length of planning horizon

The use of a planning horizon allows us to better quantify the impacts of the particular actions taken and makes it possible for imminent opportunities and variation in cost structures in future years to be accounted for. As these fluctuations in costs can be major deterrents/incentives for pipe replacement, a planning horizon can help better allocate resources over time while realizing the presence of such scenarios.
Note: A sample mathematical formulation for the top-down optimization problem is shown in APPENDIX B.

II. The **second step** of the proposed decision-process uses the results of the top-down optimization (the percentage of the pipe lengths within a class needed to be replaced or maintained), and the knowledge of the engineering and operational staff to pinpoint particular opportunities (due to road repaving, 3rd party construction, etc.) and threats (e.g. pending leaks, previous and upcoming 3rd party constructions). This allows for the selection of the most risk-prone pipes within each class, which sum up to the percentage arrived at in the first step. Since some of the segment-specific information cannot be effectively captured in the optimization procedure, the second step allows the operators to use their local insights within the purview of a risk-based cost-effective decision making system.

The composition of the pipe segments within each Asset Family Classes may change each year as segment attributes, environments and threats vary, which may result in some of the segments moving from one class to another. While some of the changes are driven by the maintenance and replacement actions done in the previous year, changes in construction cycles may also cause the segments to shift classes. Similarly, as more data are collected, the transition probabilities will also be updated.

**vii. Classifying Segments and Populating the Data Fields of Asset Family Class**

Information about pipeline segments is collected continuously, as maintenance actions are performed, third party projects are encountered, or other threats to individual segments are recognized. Information about segments is thus continuously assembled.

**Data Storage**

As mentioned, PHMSA expects that all aspects of a company’s integrity management plan should improve over time. PHMSA has identified operational performance measures, about which a company is to report annually and PHMSA expects to see improvements in performance over time. The underlying assumption is that the integrity management paradigm will produce performance improvements. This
will only be possible if better data become available over time (to fill gaps, replace initial estimates as well as expert elicitation) for segments under active management.

The net effect of PHMSA regulations is to push the gas industry toward a more data-centric approach for asset management, over time. The long term goals for the association of data to individual segments are outlined in the regulation\(^2\) and these include:

- Segment attributes (which implies location, operating pressure, material & age)
- Segment environment (which implies information that characterizes the soil, the pavement extent, distance to and density of buildings, as well as the presence of buildings of public assembly)
- Segment history (which implies historical O&M information - such as leak history and inspection/condition reports),
- Threats to segment, (which implies information that characterizes the propensity for integrity to degrade over time or the existence of third party construction activity)
- The potential impact of a potential threat, so as to quantify the resultant risk relative to other threats
- Actions taken to mitigate risks on a segment basis

Applications for data include:

- The need to quantify threats and risks on a relative basis and identify potential actions that would mitigate these risks and to use these for decision-making
- A need to produce a variety of reports
- A requirement to maintain documentation that demonstrates compliance for the preceding 10 years\(^3\)

These requirements suggest that the gas distribution industry’s integrity management programs would be best supported by a computer database that associates available information to individual pipeline segments. Because most operational data have some sort of geospatial reference (like an address) the user interface of a distribution integrity management system is likely to include a

\(^2\) Revision to 49 CFR 192 dated December 4, 2009
\(^3\) Ibid 193.1011
Geographic Information System. Data collection is therefore a discipline that requires organizational commitment and will be accomplished over a long-term time horizon.

The next logical step is the structuring of a database as a repository of information about pipeline segments (which are to be identified to belong to a specific asset family). This will require that the pipeline network be segmented. Such a database would benefit from the use of a geographic information system as it facilitates the attachment of previous historic information (such as leak and inspection information) that has a geographic reference (such as an address) through geo-coding software.

**viii. Conclusion**

In defining the data storage requirements for the integrity management plans, the emphasis of the long term objective of the PHMSA regulation is on continuous improvement. Hence in the long run, it is possible that some companies may be able to establish a more data-centric setup which can then lead to a bottom-up structure of decision-making.

In our approach, the short term requirements for data do not necessitate segment-based information on all pipes, as the macro-level evaluation involves SMEs and the concept of asset family classes to make use of the available information to develop insights in an aggregate fashion. The proposed approach, while addressing the short term requirements of the regulation with regard to risk-based resource allocation, also provides the companies with a risk-based prioritization for future data-collection, so as to further improve their decision-making process. As more data become available, the classes can become finer, and eventually the decision-making process may end up resembling a bottom-up approach.
VII. Recommended Guidelines for the Implementation of a Top-Down Risk Management Approach for Gas Distribution Pipelines

One of the cornerstones of IM legislation is the need to make decisions about individual pipe segments to improve operational safety – above and beyond existing prescriptive safety regulation. This means that operators must be able to recognize the consequences of threats (to individual pipe segments) that might result from fairly unique characteristics (pipe attributes and installation environment).

1. Create a Database

Pipe segments have attributes, a location, maintenance histories and inspection information. They are exposed to threats that are random in nature (like third party construction). Or, they might be subject to threats that are systematic and can be predicted or inferred from their life history. Expert operational staff will be able to offer insight about ‘classes’ of segments – based upon the similarity of their characteristics and situation to other pipe segments they are managing in their network. In short, a substantial amount of information is going to be available for some sector of your network, today. As time passes information will grow, geometrically. This information as well as decisions and (risk mitigation) actions taken must be maintained over a long period of time. Therefore the development of a robust and sustainable method to organize and store information about individual pipe segments is an important task that has long-term implications.

The basic approach to developing a database is to break your network into segments, associate a unique identifier (segment ID) with each segment and then assemble all of the information that you might have (asset information, maintenance history, mark-outs,
pending third party construction projects) with that segment. Information that might be collected about a segment is listed in Appendix C (Sample Database Fields). The purpose of segmentation and data association to that segment, is to map a segment into a specific ‘Asset Class’ The effort is recognized as a new requirement by PHMSA, one that starts with little information - but one that will improve over time. In the methodology proposed under this study data assembled for a segment will be used to classify each segment.

2. Segment Network:

A segment represents the smallest section of pipeline upon which management action would be taken (through the investment from the capital) to ameliorate risk. Segmentation is an important task in the implementation of any infrastructure risk management system and it can be accomplished through two different fundamental approaches. In the first approach, the entire network could be segmented at one time (facilitated by a GIS and regardless of the availability of the asset information). An alternate approach would be to create segments (unique for a section of pipeline, and to which all historic and subsequently collected information would be attached) as asset and maintenance information becomes available, through normal operations. Either approach requires the development of a convention for creating segments along with the uniform application of this construct forever, and without (substantial) modification. The development of segmentation convention that is based on the smallest possible pipe length (upon which you would take actions to mitigate risk) is recommended

3. Define Classes
Classes represent specific situations (pipe characteristics, in a specific environment that are exposed to a certain threats that are likely to produce a set of consequences) upon which priorities will be established (through optimization) and resources will be made available (also through optimization) to take action (to mitigate risks). Classes are defined by experts in the company once; they are then utilized by operational staff. Classes should be reviewed and improved through a structured process that is executed on periodic bases (say every five years). Asset classes are described in detail in section VI.B.i.

4. Map Segments into classes

Once a segment philosophy is established and classes have been created, it is time to associate a class with each of the segments.

a. The first step in the segment - mapping process is to assemble internal data and associate this data with a specific segment. If a machine facilitated process is used (such as a GIS) then records that include a physical address can be geo-coded and then associated with the segment (which would be defined by a range of geo-codes).

b. Identify data gaps

   i. **Interview Experts** Much information about segments will be available through the operational staff that has been maintaining these segments. It is likely that the asset class structure can be used to set a priority on the need to collect more information and what time scale this collection process should take. In short, vulnerable segments exposed to threats that produce significant consequences should be examined in more detail, first.

   ii. **Collect new data** The primary concern of IM regulation is to demonstrate a reduction in risks to the public. Third party construction has been identified
as a primary risk. Thus all information about third party activity needs to be associated with a segment that represents known risks - including (but not limited to) mark-out information and pending third party construction. Mark-out information is maintained by one-call agencies and was identified by PHMSA (in the discussion preamble to the final ruling) as information that should be utilized for risk mitigation decisions.

Gas distribution operators have long monitored municipal construction. An opportunity for improvement, however, exists in the application of a comprehensive and systematic construction coordination approach. One such approach is discussed in Appendix D

5. Run Optimization

Once classes have been defined the first step of the ‘top-down’ optimization process can then be executed. This process defensively allocates resources to classes and establishes priorities for risk mitigation actions. This step is described in detail in section VI.B.vi and in Appendix B. The output of the first step is a set of aggregate recommendations: the fractions of pipe segments to be replaced (or maintained) within each asset family class.

6. Implement recommendations

With a structure in place for recognizing risks, identifying priorities and the need for action – projects need to be created to specifically address unique risks on specific segments. These are the traditional construction project planning processes in place today. The sum of the segments selected for replacement within each asset class must be consistent with the fractions identified in the previous step.

7. Reclassify Segments
Threats can be systematic (age related) random (maintenance on a parallel utility owned third party) or periodic (such as the entire replacement of a third party utility). Some of these threats will change through time – they may increase or they may disappear (for example, when parallel construction is complete). Thus, the asset class assignment of many segments will change as a result of mitigated risks and other actions taken. Segments subject to changing threats will need to be reclassified (say, on an annual basis).

8. Initiate New Cycle

At the end of the company’s planning cycle (usually defined by budgeting) the cycle of optimization and risk mitigation decision-making (as defined in steps 4 through 7, above) will begin again.

9. Continuous Improvement

At the end of 5 years implementation and use of the ‘top-down’ optimization approach classes should be re-assessed – resulting the potential creation of new classes (as defined in Step 3, above) with greater granularity of definition and potential risk mitigation actions.
Appendix A: Sample Questions for Subject Matter Experts

Example of an Asset Family Class

- Cast Iron Pipe, 4 inch in diameter and below,
- Operating at low pressure,
- That has previously experienced a break,
- Previous breaks or leaks have been classified as Leak Classification 1/1a, and
- This segment is located in an area of frequent construction (repair and replacement) on utilities owned by third parties.

Sample Questions

1. Corrosion
   
   Overview (for illustration only) of SME Vision: Cast iron pipelines are generally resistant to corrosion. Cast iron is composed of elements (usually Manganese, Carbon, Sulfur and Silicon) organized in a crystalline structure (as are all metals). When exposed to certain environmental threats (for a very long time) the iron elements in the metal matrix can convert to iron oxide – leaving the carbon behind (in the form of graphite) which maintains appearance and structure of a cast iron pipe – but without offering the necessary strength. This condition is not common - although it can be observed on an individual pipe segment through destructive (scoring or striking the pipe) or nondestructive testing (such as the SWRI graphitization detector). The construction of this class will rely upon expert elicitation to define the prevalence of the threat attributed to graphitization.
Questions for SME evaluation (illustration purposes only)

- A cast iron pipe, which has recently experienced a break, has been inspected. It is found to exhibit no softness or pitting – how many years would it take for the next break to occur?
- A cast iron pipe, which has recently experienced a break, has been inspected. It is found to exhibit limited areas of surface softness as well as minor surface oxidation and limited pitting – how many years would it take for the next break to occur?
- A cast iron pipe, which has recently experienced a break, has been inspected. It is found to exhibit large areas of surface softness, surface oxidation and generalized corrosion – how many years would it take for the next break to occur?
- A cast iron pipe, which has recently experienced a break, has been inspected. It is found to exhibit large areas that are both soft and deep; oxidation deposits are present as well as significant pitting – how many years would it take for the next break to occur?

2. Natural Forces:
   Overview (for illustration only) of SME Vision: Cast iron pipelines were generally installed prior to 1950 and as such are usually associated with older established sections of cities and towns.

   Natural forces, such as landslides, are not associated with urban environments and provide no appreciable threat to pipeline segments in this class.

3. Excavation Damage:
   Overview (for illustration only) of SME Vision: Excavation is the primary threat to the integrity of cast iron pipelines. These threats fall into three categories: excessive loads on the street surface by excavation equipment can cause cast iron pipe to crack; perpendicular crossings of a trench under an existing gas main removes soil that supports the pipe, introducing stress that can lead to breaks; and parallel trenching can allow soil movement and introduces physical stress and strain that can lead to breaks.

   - Excessive Loads
     Overview (for illustration only) The SMEs felt that small diameter cast iron pipelines, which had previously experienced a break, were particularly vulnerable to construction
loads. They decided to estimate the impact that such loads might have upon pipelines in this
class, with the following expert elicitation:

- A cast iron pipe, which has recently experienced a break, has been inspected. It is
  found to exhibit no softness or pitting. This pipeline lies directly under the path the
  excavation equipment – how many years would it take for the next break to occur?
- A cast iron pipe, which has recently experienced a break, has been inspected. It is
  found to exhibit limited areas of surface softness as well as minor surface oxidation
  and limited. This pipeline lies directly under the path the excavation equipment –
  how many years would it take for the next break to occur?
- A cast iron pipe, which has recently experienced a break, has been inspected. It is
  found to exhibit large areas of surface softness as well as minor surface oxidation
  and generalized corrosion. This pipeline lies directly under the path the excavation equipment –
  how many years would it take for the next break to occur?
- A cast iron pipe, which has recently experienced a break, has been inspected. It is
  found to exhibit large areas of graphitization that are both soft and deep; oxidation
  deposits are present as well as significant pitting. This pipeline lies directly under the
  path the excavation equipment – how many years would it take for the next break
to occur?

- Perpendicular Crossing
  Overview (for illustration only) The SMEs felt that small diameter cast iron pipelines,
  that had previously experienced a break, were particularly vulnerable to soil movement that
  accompanies a trench that crosses perpendicularly and extends below an existing gas
  main. They decided to estimate the impact that such loads might have upon pipelines in this
  class, with the following expert elicitation:

- A cast iron pipe, which has recently experienced a break, has been inspected. It is
  found to exhibit no softness or pitting. A trench for the new main or its laterals will
  cross perpendicularly and completely expose an existing gas main – how many years
  would it take for the next break to occur?
- A cast iron pipe, which has recently experienced a break, has been inspected. It is
  found to exhibit limited areas of surface softness as well as minor surface oxidation
  and limited. A trench for the new main or its laterals will cross perpendicularly and
  completely expose an existing gas main – how many years would it take for the next
  break to occur?
- A cast iron pipe, which has recently experienced a break, has been inspected. It is
  found to exhibit large areas of surface softness, surface oxidation and generalized
  corrosion. A trench for the new main or its laterals will cross perpendicularly and
completely expose an existing gas main – how many years would it take for the next break to occur?

- A cast iron pipe, which has recently experienced a break, has been inspected. It is found to exhibit large areas of graphitization that are both soft and deep; oxidation deposits are present as well as significant pitting. A trench for the new main or its laterals will cross perpendicularly and completely expose an existing gas main – how many years would it take for the next break to occur?

- Parallel Trenching
  
  Overview (for illustration only) The SMEs felt that small diameter cast iron pipelines, that had previously experienced a break, were particularly vulnerable to soil movement that accompanies parallel trenching that extends below the gas main - for construction loads. They decided to estimate the impact that such loads might have upon pipelines in this class, with the following expert elicitation:

- A cast iron pipe, which has recently experienced a break, has been inspected. It is found to exhibit no softness or pitting. This pipeline lies in close proximity, and parallel, to a planned municipal water or sewer—how many years would it take for the next break to occur?
- A cast iron pipe, which has recently experienced a break, has been inspected. It is found to exhibit limited areas of surface softness as well as minor surface oxidation and limited. This pipeline lies in close proximity, and parallel, to a planned municipal water or sewer—how many years would it take for the next break to occur?
- A cast iron pipe, which has recently experienced a break, has been inspected. It is found to exhibit large areas of surface softness, surface oxidation and generalized corrosion. This pipeline lies in close proximity, and parallel, to a planned municipal water or sewer—how many years would it take for the next break to occur?
- A cast iron pipe, which has recently experienced a break, has been inspected. It is found to exhibit large areas of graphitization that are both soft and deep; oxidation deposits are present as well as significant pitting. This pipeline lies in close proximity, and parallel, to a planned municipal water or sewer—how many years would it take for the next break to occur?

4. Joint Failure

Overview (for illustration only) of SME Vision (note that this is an inherited behavior to this class): Excavation provides a significant threat to the integrity of cast iron joints (which has not been previously repaired). Parallel trenching can produce soil movement and consequential pipe
movement. This movement can deteriorate what remains of the original seal at the bell and spigot joint, resulting in a leak. The SME decided to quantify the threat based upon the depth and quality of the construction methodology of the parallel trench, utilizing the following expert elicitation:

- A small diameter cast iron pipe lies in close proximity to a parallel municipal water project. The trench will likely extend below the bottom of the gas main by 1 to 2 feet, but will be greater than 2 feet away from the main. How many years would it take for the next leak to occur?
- A small diameter cast iron pipe lies in close proximity to a parallel municipal water project. The trench will likely extend below the bottom of the gas main by 1 to 2 feet, within 2 feet of the pipe. How many years would it take for the next leak to occur?
- A small diameter cast iron pipe lies in close proximity to a parallel municipal water project. The trench will extend significantly below the bottom of the gas main and sheeting will be installed to prevent soil movement. How many years would it take for the next leak to occur?
- A small diameter cast iron pipe lies in close proximity to a parallel municipal project. The trench will extend significantly below the bottom of the gas main and conventional drop-in excavation ‘boxes’ will be used for personnel safety. No other measures will be taken to prevent soil movement. How many years would it take for the next leak to occur?

5. Equipment failure
   Overview (for illustration only) of SME Vision: This threat does not apply to this class. Classes are to be defined in a hierarchal manner, from the general to the more specific. Behaviors that are defined in a general class (such as small diameter cast iron) will be reused in more narrowly defined, derived classes (such as small diameter cast iron with a previous break).

6. Incorrect operations
   Overview (for illustration only) The SMEs decided to utilize national statistics on excavation damage as a basis for an estimate on what percentage of third party excavations result in contact to distribution pipelines. Further they decided to refine these statistics with an estimate of impact that such contact might have with pipelines in this class, with the following expert elicitation:

- A cast iron pipe, which has recently experienced a break, has been inspected. It is found to exhibit no softness or pitting. During the course of construction of a municipal water or sewer
project the excavator directly contacts the main – how many years would it take for the next break to occur?

- A cast iron pipe, which has recently experienced a break, has been inspected. It is found to exhibit limited areas of surface softness as well as minor surface oxidation and limited. During the course of construction of a municipal water or sewer project the excavator directly contacts the main – how many years would it take for the next break to occur?

- A cast iron pipe, which has recently experienced a break, has been inspected. It is found to exhibit large areas of surface softness, surface oxidation and generalized corrosion. During the course of construction of a municipal water or sewer project the excavator directly contacts the main – how many years would it take for the next break to occur?

- A cast iron pipe, which has recently experienced a break, has been inspected. It is found to exhibit large areas that are both soft and deep; oxidation deposits are present as well as significant pitting. During the course of construction of a municipal water or sewer project the excavator directly contacts the main – how many years would it take for the next break to occur?

7. Other concerns that could threaten the integrity of the pipeline.

   Overview (for illustration only) of SME Vision: No other concerns were identified.

   **Note: Computation of probability of a leak from expert opinion**

   The expert elicitation questions shown in the preceding section (“how long until…?) produce answers in units of years. Because each question will be asked to a number of experts, the process will result in a range of responses and a frequency of “years to event occurrence”. The frequency of years can be transformed into probabilities of a leak after t years (where t =1, 2, 3, …). In effect, the response frequencies of the SME are treated as event probabilities. This approach is well accepted and was used to obtain transition probabilities of bridge component deterioration in Pontis, the FHWA-supported Bridge Management System.


Appendix B: Sample Formulation for Top-Down Optimization

Overview

The objective of the formulation is to minimize the expected current and future costs based on the actions selected in a given year and subject to a budget constraint. The expected costs account for the maintenance and replacement costs in each of the subsequent years of the planning horizon, and the costs associated with an incident taking place. For each Asset Family Class, one can associate an approximate average cost for the different actions on pipelines in that class.

The underlying trade-off is to do nothing and not incur any replacement cost in a given year, but have a higher risk, versus doing a replacement by using a portion of the replacement budget which would lead to a lower risk. The risk is obtained by multiplying the associated failure probabilities with the associated consequences of failure (cost of human life and property damage).

Decision Variables

For each Asset Family Class, the decision variable is the fraction of facilities that should undergo a particular action. For example, if the optimal value for the class of “plastic pipes in a CBD, previously having experienced a leak classification of 1” is 0.15, this means that 15% of all plastic pipes belong to that class need to be replaced.

Note: Since the approach being used is a top-down approach, it does not specify which pipes in particular are to be replaced. In the second step, the company can make use of additional specific
information concerning cost penalties or opportunities to select the specific pipes in the family class which would collectively make up the optimal fraction for that family class.

**Formulation**

$$\min \sum_{s=t+1}^{T} \sum_{i=1}^{n} L_{i}^{s} * \overline{U}_{is} * d^{s-t}$$ (minimize risk across the network and planning horizon)

subject to

$$L_{i}^{s+1} = \sum_{j=1}^{n} \sum_{a=1}^{m} L_{j}^{s} * q_{ji}^{a} * W_{ja}^{s}$$ \hspace{1cm} (1)

$$\overline{U}_{is} = \sum_{j=1}^{n} \sum_{a=1}^{m} p_{ia}^{s} * q_{ja}^{s} * W_{ja}^{s} * (C_{i,replace}^{s} + C_{i,consequence}^{s} + C_{direct}^{s} + C_{goodwill}^{s})$$ \hspace{1cm} (2)

$$\sum_{a=1}^{m} W_{ia}^{s} = 1 \hspace{1cm} \forall i \hspace{1cm} (3)$$

$$\sum_{i=1}^{n} \sum_{a=1}^{m} L_{i}^{s} * C_{ia}^{s} * W_{ia}^{s} <= B_{C} \hspace{1cm} (4)$$

$$\sum_{i=1}^{n} \sum_{a=1}^{m} L_{i}^{s} * C_{ia}^{s} * W_{ia}^{s} <= B_{O&M} \hspace{1cm} (5)$$

$$0 <= w_{ik}^{s} <= 1 \hspace{1cm} (6)$$

$$\begin{align*}
\begin{cases}
  w_{ik}^{s} & <= \partial_{1} \\
  : \\
  w_{mn}^{s} & => \partial_{2}
\end{cases}
\end{align*}$$ \hspace{1cm} (7)

where,

- \(w_{ia}^{s}\) refers to the fraction of Asset Family Class \(i\) undergoing action \(a\) (from the set of \(m_{r}\) replacement options and \(m_{o&m}\) maintenance options) in year \(t\); this is the decision variable.
- \(L_{i}^{s}\) refers to the total miles of pipes in class \(i\), as defined in year \(t\) (the number of pipe miles in classes in year \(t+1\) would depend on the type of actions selected in year \(t\)).
- \(q_{ji}^{a}\) refers to what fraction of pipes transition from class \(j\) to class \(i\) when undergoing action \(a\).
- \(C_{i,replace}^{s}, C_{i,consequence}^{s}, C_{direct}^{s} and C_{goodwill}^{s}\) represent the replacement, consequence, direct and loss of goodwill costs for a pipe of unit length in class \(i\) in year \(s\) of the planning horizon.
- $p_{int}^s$ refers to the probability of a unit length of pipe in class $i$ failing in year $s$ of the planning horizon after undergoing action $a$ in the current year $t$
- $\bar{U}_{it}$ represents the risk for pipes in class $i$ in year $s$ of the planning horizon
- $B_C$ and $B_{O&M}$ refer to the capital and operation and maintenance budget respectively
- $C_{ia}^t$ refers to cost/mile of doing replacement/maintenance type $a$ (including do-nothing) on a pipe in class $i$
- $\bar{\delta}_i$ refer to thresholds on the decision variables to allow for equitable distribution of resources
- $d$ refers to the discount rate used to convert the future costs to Present Value
- $T$ refers to the length of the planning horizon

Equation (1) calculates the pipe distributions across classes in year $t+1$, based on the decisions selected in year $t$

Equation (2) calculates the risk for a pipe in class $i$ in year $s$ of the planning horizon. The risk is calculated by multiplying the probability of failure with the associated replacement, consequence, direct and loss of good will costs for each section $i$. The use of a planning horizon allows for incorporating scenarios such as the increase in costs due to missing a replacement opportunity, followed by a penalty imposed by the city agency.

Constraint (3) indicates that fraction of facilities being acted upon should add up to 100% for each class.

Constraint (4) and (5) are budget constraints.

Constraint (6) bounds the value of the decision variable between 0 and 1.

Constraint (7) consists of additional constraints on the decision variables to meet certain standards or allow for equitable distribution of resources. For example, if the company requires a minimum number of cast-iron pipes to be replaced or an upper limit on plastic pipes to be replaced, such constraints can be included in the optimization routine.
Appendix C: Sample Database Fields

Pipeline Information
- Segment ID
- Material (Steel, Coated Steel, Cast Iron, Coated Steel, Plastic ...)
- Diameter
- Length
- Joint Type
- Year of Installation
- Depth of Cover
- # of Breaks (cast Iron)
- # of Leaks
- Pipe Coating
- Coating Condition
- Cathodic protection status
- Operating Pressure
- Location (from address – to address)

Environment Information
- Type of Cover (DIRT, MACADAM, CONCRETE)
- Type of Area (Residential, Industrial Commercial)
- Type of Soil (SAND, LOAM, CLAY, BOG/SILT, CINDER/ASH)
- Corrosive Soil (Y/N)
- Type of Road (STATE-HEAVY, STATE-LIGHT, COUNTY-HEAVY, COUNTY-LIGHT, CITY-HEAVY, CITY-LIGHT)
- Area Density
- Truck Route (Y/N)
- Structure type
- Distance to Building
- Does Building Have a Basement
- Is there Continuous Pavement (between the building and curb) (Y/N)
- Is there a penalty associated with excavating (through recent pavement) (Y/N)

Leak Information
- Leak ID
- Leak Date
- Leak Location
- Leak Classification (Type I ...)
- Leak Repair Status (Pending/ Repaired)
- Leak Cause (Corrosion, Defect, third Party, Outside Force ...)
- Leak_ID
- Pipe Segment ID
- Repair Date
- Leak on Main or Service
- Number of clamps installed
<table>
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Appendix D: Considerations on Risk Assessment

During the autumn of 2009, the Pipeline and Hazardous Safety Administration (PHMSA) issued a series of directive guidelines to create a system for reduction of pipeline failures and related injuries within the natural gas distribution industry. This followed the successful implementation of similar regulations in natural gas transmission. Most notably, the new guidelines listed five primary goals, listed as follows:

1. Infrastructure knowledge
2. Identification of threats
3. Identify and implement measures to mitigate risk
4. Measure performance, monitor results, and evaluate effectiveness
5. Periodic Evaluation and Improvement

Two additional elements were also listed; the guidelines require that the distribution industry must create a viable IMS system in accordance with the above five goals, and provide documents showing threats and assets to the best of industry’s ability.

In a reaction to these new guidelines, the Gas Piping Technology Committee (GPTC) created its own distribution integrity management program (DIMP). A brief discussion of one part of this DIMP that of asset characteristics has already occurred in section I-B (“Data Requirements of a Class”). In terms of creating a new DIMP, this report advocates the top-down approach for many different reasons, such as inability to obtain proper inventory of the infrastructure and knowledge of failure mechanisms, as well as the exclusion of expert elicitation. By contrast, many elements of the original DIMP rely on the bottom-up approach.
Within the DIMP as created by GPTC, sections three, four, and five stand as sections that need to be adjusted to move toward top-down. At the core of the argument is that the top-down asset family class is a superior decision-making element than the prioritizing risk method suggested in the DIMP, because it creates an element with an internal value of risk, as shown in Section II-A, rather than creating an awkward subjective calculation.

Section three requires an exhaustive examination of existing infrastructure, with local field engineers attempting to make accurate estimates of extremely specific characteristics. By contrast, while the asset family class is just as specific as the section three inventory, it creates a decision making process that does not require lengths of pipe to be exact by looking at assets independently of quantity. While in the initial DIMP, section four agglomerates threats, these threats are not linked to assets in a comprehensive way in section five as they are in the top-down approach. Rather, a relative ranking system is shown in terms of low, medium, or high, and a risk ranking matrix is proposed. Lastly, the discussion of consequence of failure within section five fails to create an objective metric, while the asset family class incorporates this value with a financial calculation.

A. Reliability & Risk Assessment

All man-made systems eventually fail. In an effort to classify the different sources of failure in the systems that they build (during their early effort in quality control) NASA created the concept of a reliability curve. We can use the most fundamental of these curves (the so-called bath tub reliability curve) to classify and discuss natural gas distribution pipeline failure.
Early Life Failure

Infrastructure can fail early in its useful life as a result of defects in design, the materials of construction or the quality of construction. Construction specifications, inspection and testing as well as worker qualifications are in use by the gas industry to prevent such failure. The industry has many years of experience in the design and construction of its infrastructure, and, as a result it now enjoys a relatively low rate of incidents of early life failure.

Intrinsic Life Failures

Some sources of failure are intrinsic to the nature of the infrastructure. Because pipelines are buried and third party excavators sometimes do not execute all required measures to locate utilities in their work – sites (or do not implement recommended safety precautions) third-party-damage may occur at any stage of a buried pipeline’s lifecycle.

Wear-out Failure

Some gas distribution pipelines (bare steel, for example) are known to deteriorate with age. Cast iron mains, in some situations, can experience leakage as well as breakage (under certain conditions) with advanced age. There are notable exceptions. Steel distribution pipelines that are completely coated and
properly (cathodically) protected do not experience these same age-related end-of-life processes. Pipes made of plastic materials also seem to resist age-related deterioration.

**B. Construction Coordination**

The public right-of-way is crowded with facilities owned and operated by other organizations. A survey of San Francisco, for example, revealed that over 20 different organizations own and operate assets in the public right-of-way. These assets undergo their own deterioration processes and require maintenance and eventual replacement. This third party construction presents a threat to all other existing structures in the PROW. These threats can be appropriately ameliorated – if proper prior notification of the third party is available.

The City of San Francisco became motivated to mitigate conflicts and risks of constriction in the PROW and legislation was passed by the city requiring collaboration and cooperation of all stakeholders. The Department of Public Works (DPW) implemented a simple procedure to develop shared construction plans for a 5 year horizon. The process begins with the identification of street pavement plans; this is followed by solicitation of construction plans of utility stakeholders and is concluded with the incorporation of resultant information in an on-line GIS. This process provides all stakeholders, both municipal and privately owned utilities, access to information about third party construction projects – that might be considered a threat to their structures – on the level of each block for the subsequent 5 year period. Here is an overview of their process:

The Notice of Intent (NOI) and Final Preliminary Plan (FPP) letters are documents used by DPW to provide information about a planned DPW capital project including the work scope, project limits, the estimated construction schedule and time frame. The NOI/FPP solicits information from each utility company and city agency that excavates within the Public Right of Way (PROW). The solicited
information includes a request for information about upcoming planned projects, work around support information and as-built information.

DPW currently hosts monthly CULCOP (Committee for Utility Liaison on Construction and Other Projects) meetings. The members consist of a representative from each City Agency/Utility Company that has planned Capital Projects scheduled to be constructed within the PROW. The purpose of the meetings is assist with the scheduling of utility work that is connected with Department of Public Works projects.

DPW has created a database called the 5 year plan. The data consists of planned capital projects scheduled to be constructed within the PROW. City legislation (Excavation Code order no. 176-707) requires each City Agency/Utility Company to enter their capital projects into the 5 year plan. Each City Agency/Utility Company is also required to coordinate their planned projects with other projects that are identified in the 5 year plan. Please review the link to the Excavation Code for further information regarding this requirement.


Current reports from the database are available through the DPW web site: http://www.sfdpw.org/index.aspx?page=370 and a sample of one such report (in a partial and reduced format is included below.
The survey conducted in the current study (found in V. ‘Survey of Data’) examined the notification processes for third party construction, and if this notification allow the company to appropriately protect their facility. Here are the responses to the survey:

- 14% of respondents indicated that they do not receive prior notification from either municipal or privately owned utilities.
• 57% of respondents indicated that adequate notification is available from municipal utilities – but that privately owned utilities do not provide advanced notification.
• 28% of respondents indicated that advanced notification is provided by BOTH municipal and private utilities about their pending projects.

A second survey question examined municipal efforts to notify utilities of pending street pavement rehabilitation projects. All of the survey respondents indicated that they receive notification of pending pavement projects; 71% indicated that the notification provides adequate time to evaluate the need for and execute a gas pipeline replacement project, 29%, however, indicated that notification timing is inadequate to execute a replacement – when needed.

C. An In-depth Gas Industry Perspective on Construction Coordination

A large California utility examined their project planning processes within and between itself and 20 different organizations in its service franchise. The purpose of the California study was to

• quantify barriers to the improvement of project planning, with the goal of both reducing construction costs (by avoiding maintenance in protected streets and by seizing collaborative opportunities with municipal pavement projects) and
• Increasing public safety (by reducing third party damage that results in incidents).
• Evaluate the potential benefits that an internet-based project communication system might

The approach of the California study was to quantify business processes of the different stakeholders and to identify mutual goal for improvement. This program applied business process mapping to facilitate business process improvement by providing a holistic, visual representation of how business processes individually and collectively fit together to achieve the desired result. Mapping can be used to evaluate how a process is achieving its objective. One focus of process mapping is building an understanding of trigger events, which initiate downstream processes.
Results of Process Analysis: PROW Construction Planning

Poor communication was, indeed, pinpointed by all stakeholders (of the California study) as the primary risk that PROW construction projects face. A comprehensive review of these risks are summarized and discussed below.

Summary of Communication Risks

- Breakdown has process implications
  - Delayed Discovery
  - Missed Opportunity
  - Project Delays
  - Strain Internal Processes
    - Relationship Deterioration
  - Management Controls
    - Can Compromise Resource Allocation Priorities
- Safety
- Cost
  - Premiums, Moratoriums & Penalties
- Budget Management
  - Difficulties
- Working Relationships
- Quality
  - Sub-Optimal Solution

Good Communication Promotes Productivity and Efficiency

Communication provides the underpinning for all work processes. When communication is effective and efficient the process is productive - promoting the best use of limited resources. Utility construction planning is a large and complex work process. PROW construction planning stretches over several (geographically dispersed) departments (in a utility) and is dependent upon extensive interaction with many outside agencies (municipal, county and state). Because of its complexity, it is not surprising that stakeholders described many opportunities for improved communication, along with the impact of poor communication on the current processes.
One conclusion of the California project is that notification or the discovery of a third-party construction project typically occurs late in the development of the third-party project and a large percentage of the discovery of pending third party projects is through informal channels. Utility stakeholders indicated that the following hierarchy for project discovery exists.

(i) Informal communication about project from the municipality, through indirect channels (such as other impacted utilities) or acquired through information mining (practiced by many of the planning department staff).
(ii) Request for information about existing Utilities below ground infrastructure (typically encountered during their design process).
(iii) Receipt of a design document accompanied by a request for review.
(iv) Receipt of a list of future municipal projects, sometimes distributed at coordination meetings and sometimes distributed by municipalities via the mail.

The timing of discovery has a critical impact on the options considered by a utility and on the costs incurred in the analysis, design and construction process. Processes i, ii and iii are the more commonly encountered project planning triggers and these same processes result in higher costs for utilities.

Late notification, of a pending third-party project, places utilities in a difficult position, because:

(i) The third party project has little or no flexibility to accommodate change;
(ii) Any action that a utility might take:
   a. Must be done immediately and;
   b. This urgency has a negative impact upon:
      c. Organizational productivity;
      d. Inter-departmental working relations;
      e. Company-municipal relationships, and;
      f. Can result in delay-of-project penalties.
(iii) Due to the compressed timescale (associated with late notification) and the many competing demands for the limited available capital, utilities often not in a position to seize cost savings opportunities (such as replacing an aging main prior to municipal paving); and
(iv) New environmental regulations have complicated the project planning process. This has placed more demands on the utilities’ planning department and increased the amount of time a project takes to plan. Utilities can no longer respond to third party construction projects, as it once could.

A more detailed description of the impact upon construction project, as identified by Utility stakeholders of the California project, follows:
Management Control Risks

Utilities exert a variety of controls on the expenditure of capital for the investment in new infrastructure. Outside construction projects trigger a need to complete all work processes, with attendant management controls, by a date specified by an outside agency. Poor communication (delayed notification, delayed discovery or incomplete project information) impacts project control processes. The following issues were identified during process mapping:

(i) Budgetary controls: project costs are authorized (in comparison with historic costs); spending limits are set (based on project progress) and performance of the completed project is reviewed. Projects that are conducted on short notice tend to cost more than projects that proceed methodically through planning.

(ii) Design controls: the proposed design is reviewed by other departments within a utility (such as construction and the operating department). This review allows these parties to influence the project – sometimes reducing costs or improving the quality of the work. Compressed schedules can compromise the ability of a utility to review and improve pending projects.

Pipeline Safety Risks

Outside construction is the primary cause of gas pipeline incidents (i.e. damage to property and life). Incidents can:

(i) Diminish a gas utility’s “brand equity” in the eyes of customers, regulators and the communities it serves.

(ii) Embroil a gas utility in expensive law suits and expose the corporation to financial liabilities through the lack of adherence to safety regulation or company safety policies; and

(iii) Cause the passage of new, expensive operating regulations.

Financial Risks

(i) Newly paved roadways increase construction and maintenance costs for projects or activities performed subsequent to the completion of the municipal project.

(ii) Poor communication or a breakdown in the communication process can cause utilities to miss an opportunity to maintain or replace an aging or inadequate pipeline, at reduced cost.

(iii) Delayed discovery of a planned construction project, which requires utilities facility relocation:

   a. Increases cost to respond to the situation.
   b. Reduces the options available for consideration.
   c. Eliminates many cost savings opportunities otherwise available to Utilities.
   d. Can cause a delay in the sponsoring agency’s project (as Utilities may be unable to respond within the unreasonable time constraints proposed by the sponsoring agency), which may result in delay-of-progress penalties.
e. Can complicate the management of the planning department’s budget, result in changing priorities and the delay and cancellation of other important projects.

(iv) The submission of poor quality project documentation is common. A design that undergoes a substantial revision by the sponsoring agency has a compounded effect upon Utilities, causing engineering & planning staff to expend unnecessary effort, waste precious time and incur additional costs.

(v) Unanticipated franchise projects change priorities and budgets. This may cause the delay of high priority replacement projects, resulting in pipeline maintenance activities and costs – which would otherwise be unnecessary. These costs reduce the return on investment that Utilities seeks to capture with planned replacement projects.

(vi) Inadequate information from municipalities, about their own re-pavement programs may cause Utilities to:
   a. Expend additional resources to satisfy municipal paving requirements in a street under moratorium.
   b. Miss cost savings opportunities (which are potentially available by timing replacement prior to street re-pavement);
   c. Reschedule a pipeline replacement program because a moratorium is in place on the subject street; and
   d. Perform maintenance on a deteriorated pipeline (identified for replacement) during a moratorium period, incurring additional and unnecessary street reinstatement costs.

(vii) Pipeline construction costs have changed as a result of new pavement management tactics (extensive use of preventive maintenance treatments and construction moratoriums). The Utilities’ pipeline replacement planning criteria may not incorporate these new areas of costs and the duration that they are in-force (which can be up to 50% street lifecycle). In addition, information about cost-saving opportunities for pipeline replacement (such as re-pavement programs) has not been previously available and could not have been previously incorporated in Utilities’ pipeline replacement planning criteria.

(viii) The urgency of the problem constrains construction flexibility, eliminating some options that are often employed to control construction cost. Construction costs on these projects may be higher-than-average, because construction in streets with restrictions (moratoriums) may be necessary.

**Business Relationship Risks**

(i) Working relationships with municipalities may suffer, when poor communication produces artificial urgency and a need to put a solution in place by a specific date.

(ii) Working relationships with municipalities may suffer as a result of performing maintenance on pipelines, which are located under newly paved roads

(iii) Delayed discovery of a planned construction project, which requires Utilities facility relocation may strain the working relationships between the Planning Department and other Utility departments that must provide services or supplies on a compressed schedule.

(iv) In the course of this project stakeholders interviewed communicated that the concept of trust was central to many of these conversations. Trust is built slowly, through competence and integrity. It is clear that the excavation of freshly paved roadways can quickly destroy trust between municipalities and utilities. Each incident literally endures as a long term symbol of organizational breakdown in the eyes of the community. Municipal pavement managers can become the target of personal and public ridicule. Such incidents can complicate all future transactions between the municipality and the utility, for a very long time.
**Infrastructure Asset Management Considerations**

Infrastructure construction produces assets that are essential to modern life. These construction projects are “temporary endeavors” that produces a “unique” asset (with a very long life) and every individual infrastructure project involves many different stakeholders. Infrastructure systems (municipal roadway and utilities) have many unique features:

- These networks are constructed in close physical proximity to one another
  - They share a common environment.
  - The different networks are sometimes constructed of similar materials.
  - Construction on one facility often has a potential impact on another. The greatest threat to the integrity of a gas distribution system, for example, is construction on other, nearby belowground utilities.
- Belowground construction always has an impact upon the roadway.
  - The economics of repair or replacement of any belowground utility is dominated by the costs for the removal and reinstatement of the pavement located above.

As a result of these and other factors, modern infrastructure systems display many behavioral and economic interdependencies. It offers a perfect setting for collaboration. Information that is collected continuously during facility operations is used to evaluate the fitness-for-purpose of every, or nearly every, element in an infrastructure network. Today infrastructure is regularly replaced or upgraded, because:

- It has deteriorated (through its use or its exposure to the environment) and it can no longer be economically maintained;
- It has become a ‘bottleneck’ and no longer has adequate capacity; or
- Changing safety or quality regulations necessitate the renewal or replacement of this asset or element of the network.

Every utility and municipality monitors their network to determine if and when individual elements should be modified or replaced. These processes necessitate

- The collection of data from the field;
- Engineering and economic evaluation of the network and its individual components;
- The continuous evaluation of new safety and quality requirements;
- The identification of potential (alternative) rehabilitation and replacement projects;
- Priority ranking of individual projects and the management of an inventory of potential projects (sometimes called a ‘backlog’);
- Capital budgeting and the selection of individual projects for a particular budget cycle;
- An analysis of the environmental impact of individual construction projects and the submission of appropriate permits; and finally
- Scheduling of an individual project for design and construction during a particular calendar year and budget cycle.

It is common knowledge, throughout the infrastructure management community, that construction project partnerships offer significant cost savings. Operators that collaborate and form partnerships to carefully sequence their construction, to precede planned roadway construction, can capture substantial savings. This concept is simple to describe and is common practice in new subdivision construction.

It is the mission of asset management to ensure that individual elements of a network, as well as the network in total, deliver the greatest useful life at the least cost. To fulfill this goal, infrastructure
networks are evaluated continuously throughout the year; these processes are performed independently by each of the different network owners-operators. The complexity and independence of these different asset maintenance and replacement processes makes collaboration difficult. Today, most utilities become aware of construction projects, of other infrastructure owners, late in the development cycle of that project. In the past, many organizations were able to respond to projects opportunities on short notice. This is no longer the case, as organizational change, aging infrastructure (which places more demands on capital) and new regulation have created a new environment need for access to construction planning information early in the planning cycle.
Appendix E. References

SF’s Pavement Management Program: http://www.mtc.ca.gov/services/pmp/


"2006 Downtown Minneapolis Traffic Volumes" (PDF). Minnesota Department of Transportation. 2006.


